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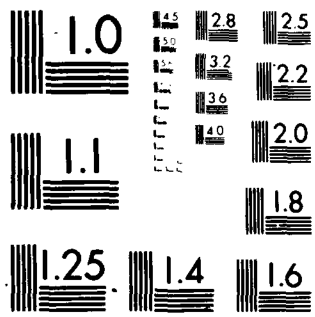

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CIVIL ENGINEERING LABORATORY
Naval Construction Battalion Center
Port Hueneme, CA

Sponsored by
NAVAL FACILITIES ENGINEERING COMMAND

ASSESSMENT OF THE MORISON EQUATION

July 1980

An Investigation Conducted by
WOODWARD-CLYDE CONSULTANTS
7330 Westview Drive
Houston, TX

N68305-80-C-0007

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER CR-80.022	2. GOVT ACCESSION NO. AD-A088185	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Assessment of the Morison Equation.		5. TYPE OF REPORT & PERIOD COVERED Final; Survey to report date
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Woodward-Clyde Consultants		8. CONTRACT OR GRANT NUMBER(s) N68305-80-C-0007
9. PERFORMING ORGANIZATION NAME AND ADDRESS Woodward-Clyde Consultants 7330 Westview Drive Houston, TX 77055		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS YF59.556.091/01.501
11. CONTROLLING OFFICE NAME AND ADDRESS Civil Engineering Laboratory (Code L44) Naval Construction Battalion Center Port Hueneme, CA 93043		12. REPORT DATE Jul[redacted]80
		13. NUMBER OF PAGES 175
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited. 16 F59556		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Ocean waves, Wave forces, Wave kinematics, Morison equation, Drag coefficient, Inertia coefficient, Inclined structures, Structural shapes, Surface roughness, Interference, Transverse lift force, Hydroelastic interaction, Research needs		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) A critical assessment of the Morison equation is provided. The Morison equation is used to calculate the loading on offshore structures due to ocean waves. The assessment covers both the original equation and the modifications currently in use by industrial designers. A review of the literature is provided. It is concluded that the Morison equation provides an		

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adequate design tool provided careful consideration is given to the selection of the fluid kinematic representation and the empirical coefficients. Improvements in the accuracy of the operation can be achieved through research leading to (1) improved descriptions of the sea state, (2) better representations of the water particle velocities and accelerations in combined wave-current flows, (3) improved quantification of the drag and inertia coefficients, and (4) inclusion of the fluid-structural interaction.

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TABLE OF CONTENTS

TABLE OF CONTENTS (Cont'd.)

TABLE OF CONTENTS (Cont'd.)

TABLE OF CONTENTS (Cont'd.)

ASSESSMENT OF THE MORISON EQUATION

1.0 INTRODUCTION

1.1 Overview

The Morison Equation, derived 30 years ago, is an engineering model used to determine wave forces on structures. Given the geometry of the structure, the water particle velocities and accelerations, and two empirical coefficients (inertia and drag), the model allows the engineer to compute hydrodynamic forces. The equation was based on a highly idealized and simplified characterization of water, waves, structures, and the physics of the flow of water around structural elements.

The Morison Equation has become one of the cornerstones of ocean engineering. It has been used to design literally thousands of offshore structures. It is an integral part of virtually every current code or guideline for design of offshore structures.

In the 30 years since the introduction of the Morison Equation, our general understanding of waves, wave forces, and the flow of water around structural elements in ocean settings has improved dramatically. Extensions to the Morison

Equation have been investigated and, in some cases, applied in the design of ocean structures.

An objective of this study has been to assess the extent to which the Morison Equation should be applied in the design of Naval offshore structures. A second objective of the study has been to identify those areas of research and development that could lead to important improvements in the applications and reliability of the existing model, or which could lead to the development of new analytical models.

1.2 Scope

This study has directed its primary attention to the engineering design aspects of the Morison Equation. To the designer of Naval offshore structures, the design process is intended to produce structures having desirable performance and acceptable costs. By necessity, the design process must represent a realistic simplification of the complex physical processes and uncertainties involved in the future interactions of a Naval structure with its ocean environment.

In contrast to the design process, the research process focuses on development of accurate representations and characterizations of the complex realities of the interactions of a structure with its ocean environment. Ideally, the results of the research process are distilled in a timely way into the design process, making the complex simple, and the uncertain certain, while preserving levels of safety at acceptable cost.

The Morison Equation was originally proposed in the context of a design process. The primary question is: in the light of current knowledge, does the model represent a realistic and reasonable characterization of the physical processes associated with the interactions of offshore Naval structures with ocean waves and currents?

Some care must be taken to distinguish between the specific perspectives of the Naval Civil Engineering Laboratory and the perspectives of private offshore structure design firms and industrial groups. Also, it is necessary to carefully distinguish between the original Morison Equation, which is very close to the form presently used in the Navy's design procedures, and the other forms of the Morison Equation which represent the state of practice of the commercial offshore industry. Various advanced forms of the Morison Equation currently are in use by industry. These forms depend on the particular problem at hand, as well as the experience of the particular design firm or its engineers. In many cases, this experience is shielded from the Navy by proprietary restrictions. Consequently, it is necessary to synthesize and summarize these Morison Equation-based procedures before the limitations and areas for potential advancement of present uses of the equation can be clearly documented and presented.

It must also be kept in mind that an evaluation of the Morison Equation depends on the particular needs of the user. Conservative design may be acceptable to petroleum industry platform owners, as the platforms must support personnel and expensive equipment, as well as producing an income-generating and essential public resource. However, for Navy facilities, when automated and unmanned offshore platforms are needed, the conservatism may not be warranted. This difference in perspective causes the need for a full explanation of the strengths and weaknesses of the present state of practice design methods utilizing the Morison Equation.

It is at this point that three other aspects of scope of this study must be introduced.

1. In this study, the Morison Equation has been examined in the context of offshore structures. Structures located within the surf or coastal zones have not been considered.

2. The equation has been examined in the context of offshore structures that are comprised of elements that are small relative to the waves that produce hydrodynamic forces of primary concern. Large breakwaters and monolithic structures (similar to concrete gravity platforms installed in the North Sea) are beyond the scope of this study, and fundamentally are beyond the scope originally intended for the Morison Equation.

The study does include consideration of fixed Naval ocean structures. This class of structures includes bottom-supported platforms in deep and shallow water, sea-floor connected or tethered floating platforms, and pipelines.

3. The third aspect of scope concerns the quantifications that are required as input to the Morison Equation. This study has been directed primarily at an assessment of the competency of the Morison Equation itself. The descriptions of structure geometry and water particle velocities and accelerations, although important, are beyond the primary scope intended for this study.

It must also be recognized that the Morison Equation represents only one step or part of a process intended to result in characterizing wave forces appropriate for design of Naval structures. In a very generalized and simplified sense, this process proceeds through six steps:

1. Characterization of the sea state of design interest.
2. Characterization of the water column kinematics associated with the design sea state.
3. Characterization of the structure (including geometry, roughness, stiffness, mass, buoyancy, strength, energy dissipation characteristics).

4. Characterization of the interactions of the structure with the motions of the water column.

5. Definition of the empirical coefficients (drag and inertia) incorporated in the Morison Equation.

6. Characterization of the hydrodynamic forces on the structure utilizing the Morison Equation or model.

1.3 Summary

This section summarizes some of the principal findings developed during this study.

The original Morison Equation has undergone a series of modifications since it was introduced. These modifications have altered the form of the terms in the equation. Furthermore, the use of the equation depends very much on the appropriate choice of the force coefficient values as well as the particular way in which the structural elements and wave kinematics are treated. At present, the Morison Equation cannot be described or evaluated without full reference to the context of the design problem and form of the equation considered.

In this context, the Morison Equation has proved to be a useful tool for computing design wave forces on certain types of offshore structures. Its future use seems assured. As stated in Section 1.2, the Morison Equation must be viewed as a design-oriented model. Further, it must be viewed as one part of an overall process intended to develop design wave force descriptions.

This study indicates that use of an advanced form of the Morison Equation in the design of a given class of Naval offshore structures is warranted. Coastal or surf zone facilities are excepted, as are very large breakwaters or monolithic structures that have geometries comparable with those of the design waves. Sections 3 and 4 discuss the operating regimes where present data and information indicates that the equation is and is not applicable or is questionable.

The principal concerns with the Navy's future use and development of Morison Equation-based design procedures focus on:

1. The modernization of the Navy's design standards to bring them in line with the more advanced methods and practices of the offshore industry.
2. Consideration of NCEL toward developing a central role in the government's guidance, support and development of research and development activities based on extending and eventually replacing the Morison Equation.
3. Supporting research leading to better description of the water particle velocities and accelerations, given the characterization of the sea state and the structure interacting with that sea state.
4. Supporting research leading to better quantification of the empirical coefficients.

5. Encouraging basic research on the fluid dynamics of oscillatory flow around structural members.

The first two items listed above require NCEL to define its objectives in the pragmatic question of its requirements in designing or evaluating the design of future Naval offshore structures, as well as its role in guiding the advancement of research and development in the area of computing wave forces on ocean structures. Much of the research and development on this subject is presently in the hands of industry. This limits the access of the Navy to the most up-to-date advancements. Furthermore, the Navy's needs and requirements are not identical to those of the offshore petroleum industry.

The research intended to improve the descriptions of the sea state and the associated water column kinematics focuses on characterization of the sea surface to include the changing form of progressive waves, the short-crested directional-spreading characteristics of waves and breaking waves in time and frequency domains. This research should also include efforts directed toward improved descriptions of nonwave water column motions and their interactions with the wave-induced motions. This research would involve analytical, laboratory, and field measurement efforts.

The basic research on fluid-structure interaction dynamics, fundamentally, would have as its objective the development of new analytical models. This effort would first attempt first

characterize the physics of water flow around structure elements in ocean environments. The second phase of this effort would be to develop those analytical models which would describe such flows.

1.4 Report Structure

The original theoretical background and assumptions involved in the formulation of the Morison Equation is first presented in Section 2 of this report. The current interpretations of the Equation and its applications in design are then discussed in Section 3, together with an introductory overview of the basic mechanics of fluid flow process about cylinders. An account of the different operating regimes and problem areas where the equation is and is not applicable is also presented in Section 3. Section 4 discusses the limitations of the Equation and its extended usage in treating special problem areas. In Section 5, an account of various possible research efforts for bridging the limitations and expanding the applicability of the Morison Equation is presented. Critical evaluation of different research efforts is given in Section 6, and recommendations on future research directions are given in Section 7. A summary of the findings and conclusions of this report is given in Section 8.

2.0 THE ORIGINAL MORISON EQUATION

Stokes (1851), in a paper on the motion of a pendulum in a viscous fluid, showed that the force exerted by a fluid on an accelerating body was composed of two parts: one depending on friction effects, and one depending on the inertia of the displaced fluid. Morison, O'Brien, Johnson and Schaaf (1950) demonstrated in an experimental study the existence of the two components in the forces due to wave motion acting on submerged piles. The following sections attempt to present the original theoretical background and assumptions involved as used by Morison, et al, in the formulation of the Morison Equation. Formulations for the total force and moment on a vertical circular member are also derived using the Morison Equation and the Airy Linear Wave Theory.

The force per unit length, F, on a vertical pile exerted by unbroken surface waves as shown in Fig. 2.1 can be formulated by the so-called Morison Equation as follows:

$$F = C_D \, 1/2 \, \rho \, Du^2 + C_M \rho \frac{\pi D^2}{4} \dot{u} \qquad (2.1)$$

where D = pile diameter

ρ = water mass density

C_M = coefficient of inertia

C_D = coefficient of drag

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*The u^2 term is now generally replaced by $|u|u$ to ensure that the drag force component is in the same direction as the velocity.

u = horizontal component of orbital fluid velocity

$\dot{u}$ = horizontal component of orbital fluid acceleration, $\partial u / \partial t$

In formulating this equation, Morison, et al (1950) assumed that the horizontal wave force exerted on the vertical pile was composed of two parts:

1. A drag force proportional to the square of the horizontal component of water particle velocity and
2. A virtual mass force proportional to the horizontal component of the accelerative force exerted on the mass of water displaced by the pile.

The term "virtual mass" may be explained as the increase in force caused by an increase of the displaced mass of the fluid when an object is accelerated in a fluid, as compared to acceleration in a vacuum. Thus, in accelerated flow there is an apparent increase in displaced volume without any actual increase in the mass of the object.

Application of the equation depends upon the knowledge of water particle motion, and upon empirically determined drag and mass coefficients. The magnitude of horizontal particle velocity, u, and horizontal particle acceleration, $\dot{u}$, is determined as originally proposed by Morison, et al, by the Airy linear wave theory. However, the Morison Equation can in general be used with any wave theory.

In the development of the above theoretical relationship, the following assumptions were made by Morison, et al:

1. The equation is for unbroken surface waves.
2. The equation is for a single vertical, cylindrical object, such as a pile, which extends from the bottom upward above the wave crest.
3. The diameter of the pile is small compared to the wave height, wave length and water depth.

In comparing Equation 2.1 with experiments, Morison and his co-workers found that for any specific experiment with specific wave parameters and a particular cylinder diameter, values of C_M and C_D could be chosen such that Equation 2.1 gave good agreement with the measured force time history.

A study of the Morison Equation, based on linear wave theory, permits several useful observations to be drawn:

1. The drag force decreases with increasing distance below the wave surface more rapidly than does the inertia force.
2. The relative importance of the drag force decreases with increasing ratio of pile diameter to wave height.
3. The two components of the total force, inertia and drag force are out-of-phase. When the crest passes the pile ($\theta = 0$), the drag force is maximum and the inertia force $F_I = 0$. When the instantaneous water surface elevation is near the still water level ($\theta = \pi/2$), the drag force

$F_D = 0$, and the inertia force is maximum. This information has been widely used in experimental investigations of the force coefficients concerning oscillatory flows such as waves.

The Morison Equation is important to offshore technology because it provides a basis for predicting fluid loadings due to waves, which are a crucial consideration for designing ocean structures. Government and industry regulatory bodies such as the American Petroleum Institute (API), the United Kingdom Department of Energy (DOE), and Det Norske Veritas (DnV) of Norway all have recommended the use of the Morison Equation in designing offshore structures. Much work has been done since 1950 which has led to changing ideas about the interpretation of the equation, but the basic principle of a force divided into a velocity dependent drag component and an acceleration dependent inertia component is still the cornerstone of conventional practice.

3.0 APPLICATIONS OF THE MORISON EQUATION

3.1 Current Interpretation of the Morison Equation

The derivation of the original Morison Equation, as discussed in Section 2, was based on a problem of limited scope. The original work warned that the "paper is essentially a preliminary report submitted at the time (1950) because of the current importance of wave forces in the design of offshore structures". Users of this equation should be aware of its validity and applicability of the basic assumptions upon which the equation rests.

First of all, the basic assumption of the Morison Equation that wave forces on a cylindrical member can be separated into a velocity-related drag term and an acceleration-related inertia term is a simplification of the complex fluid-structure interaction problem. The equation neglects the time history of the fluid flow and the complex unsteady vortex action that is associated with most of the design flow-structure conditions. The equation cannot fully account for flow-structure conditions that are complicated by roughness, inclined members, transverse lift forces, near surface effects, and interference effects due to neighboring elements, etc. The equation also cannot represent irregular kinematic conditions where the flow is complicated by breaking waves, wave-current interactions, and three-dimensional sea states. Instead, the Morison Equation depends on a pair of adjustable force coefficients to obtain good matching between

measured and calculated forces. It is also the inexact nature of the equation that causes the force coefficients to depend on flow-structure parameters that are different from one application to another. A more detailed discussion on the validity of the Morison Equation is provided in Section 3.6.

In the following three decades after the introduction of the Morison Equation in 1950, the general understanding of wave flows around structural elements has improved immensely. However, a more appropriate formulation to replace the Morison Equation still has not been found. Current practice still relies heavily on the Morison Equation or its extended form to determine wave forces on structures. However, the original formulation has undergone a number of modifications and extensions to broaden its usage. One example is to rewrite the equation into a more general form, replacing D by a characteristic cross-sectional area per unit length, A, and $\pi D^2/4$ by volume per unit length, V, for structural elements other than circular cylinders, as

$$F = C_D \frac{\rho}{2} A |u| u + C_M \rho V \frac{Du}{Dt} \tag{3.1}$$

An absolute-value symbol, $|u|$, has been added to ensure that the drag force component is in the same direction as the fluid particle velocity. The use of the substantial derivative to describe the fluid acceleration, Du/Dt, has been found to yield

better verification than the local acceleration $\partial u/\partial t$ (Isaacson, 1979) in computing the inertia forces.

Recognizing the inexact nature of the Morison Equation, it is also common practice for designers to inject bias factors into the equation based on individual judgment and structure survival experience. An extended form of the Morison Equation including bias factors can be written as

$$F = K \left[K_D \, C_D \, \frac{\rho}{2} \, D \, u|u| + K_M \, C_M \, \rho \, \frac{\pi D^2}{4} \, \dot{u} \right] + C \tag{3.2}$$

where K, K_D, K_M, C are different levels of bias factors to account for varying degrees of uncertainties not fully accounted for by the original Morison Equation.

In light of current improved knowledge on wave flows about structures, extensions to the Morison Equation have also been investigated to accommodate complications such as inclined members, transverse lift forces, near surface effects, interference effects, etc. The Morison Equation has also been modified to represent both in-line and transverse forces (resulting from net circulation often called "lift" forces). It is also commonly modified for use as a spectral transform function between frequency domain characterizations of wave kinematics and structural response. These extensions are further discussed in Section 4 of this report.

These modifications of the "original" Morison Equation cause us to adopt a special use of the name in this report. In the following sections, the term "Morison Equation" can refer to either a particular formulation of the equation, or to the whole range of generically related formulations which are presently in use. The context in which the name is used must be kept in mind if the reader is not to suffer from this ambiguity.

At this point, it is important to emphasize that the Morison Equation is an empirical engineering model. Its applicability and correct usage are only limited to conditions where its assumptions and limitations are observed. An understanding of the range of operating regimes where the Morison Equation is, and is not, applicable is essential to practicing offshore structure designers. This aspect will be further discussed in Section 3.3 of this report.

3.2 Basic Background for Fluid Flow About Cylinders

A brief review of the basic characteristics of fluid flow about circular cylinders will serve as useful background for the discussions presented later in this report.

Fluid flows can be classified as either ideal flow or real flows. Ideal flow can be defined as that which occurs in a nonviscous and incompressible fluid. The ideal fluid flow field can be fully described by a velocity potential. A force formulation such as the Morison Equation can be used in calculating ideal fluid forces on a circular cylinder by setting

the drag coefficient to zero and the inertia coefficient to 2.0.

In real sea situations, although water is highly incompressible, the viscosity of the fluid results in substantial differences between ideal and real flow fields. The primary effect of viscosity on fluid flows about circular cylinders is the occurrence of a boundary layer and flow separation regimes in the flow field around the cylinder.

Consider a viscous fluid accelerating from rest and flowing past a circular cylinder. When the fluid starts to move, the flow is laminar, and there is no separation. As the flow accelerates, the fluid friction due to viscosity acting near the cylinder boundary retards the fluid particles. This retarded fluid does not contain enough energy to continue to accelerate against the increasing pressure on the downstream half of the cylinder. Separation results, and a low pressure regions occurs in the resulting near wake.

3.2.1 Steady Flow

Many important aspects of the complex flow caused by waves acting on a structural member can be best illustrated by first exploring the nature of steady flow past a cylinder. For a circular cylinder in steady flow, there are several distinct flow regimes characterized largely by the behavior of the flow in the boundary layer, in the wake, and by the positions of boundary layer separation. For a smooth circular cylinder in steady flow, these flow regimes may be conveniently distinguished by a

dimensionless flow parameter called the Reynolds number, Re. The Reynolds number is defined as UD/ν, where U is the flow velocity, D is the cylinder diameter, and ν is the fluid kinematic viscosity. In steady flow, the drag coefficient, C_D, has been found to be correlated with the Reynolds number as shown in Fig. 3.1 for smooth cylinders. Four different flow regimes are also shown in Fig. 3.1 that are delineated by the Reynolds numbers (Achenbach, 1971). The transitions between regimes depend on disturbances present in the approaching flow.

a. Subcritical regime: $Re < 2 \times 10^5$

In the subcritical regime, the boundary layer is laminar from the flow stagnation point through separation zone which occurs at about 80 degrees from the stagnation points. The rather wide wake structure and low base pressure resulting from the separation, even before the maximum breadth of the cylinder, leads to a rather large drag coefficient (about 1.2) throughout this regime.

b. Critical Regime: $2 \times 10^5 < Re < 5 \times 10^5$

When the Reynolds number increases to the critical regime, the laminar boundary layer becomes turbulent. The turbulent boundary layer separates farther upstream on the cylinder due to increased shear stress, and the wake narrows. This narrowing of the wake results in an increased base pressure and a dramatic drop of the drag coefficient (from 1.2 to its minimum value of about 0.3).

c. Supercritical Regime: $5 \times 10^5 < Re < 5 \times 10^6$

On further increases of Reynolds number, to the supercritical regime, the transition to turbulence moves ahead of the laminar separation point. As the turbulent portion of the total length of boundary layer between the stagnation point and the separation point increases, the thickness of the boundary layer arriving at the adverse pressure region increases. Since thick boundary layers are more susceptible to separation in an adverse pressure gradient than thin boundary layers, increasing the Reynolds number results in moving the separation point towards the stagnation point and increasing the width of the wake. This contributes to decreasing the base pressure and an increasing drag coefficient which is characteristic of the supercritical regime (Garrison, 1980).

d. Post-Critical Regime: $Re > 5 \times 10^6$

At very high Reynolds number, the separation point moves very close to the stagnation point, and therefore, its location becomes insensitive to further increases of the Reynolds number. At this post-critical regime, the drag coefficient approaches a constant value (about 0.6-0.7).

3.2.2 Oscillatory Flow

The nature of flow is much more complex for a circular cylinder in waves than in the steady flow condition, and a well-defined relationship between the drag coefficient and Reynolds

number do not exist. In particular, the flow close to the cylinder is likely to be strongly influenced by two specific flow phenomena not present in steady flow: the water particle motions are orbital, and the oscillatory nature of the flow causes the wake of the cylinder to be swept to and fro over the cylinder. The boundaries between the flow regimes in oscillatory flows and the associated fluid behavior are not clearly established as those in steady flows. However, the published values of drag coefficients in waves still show an overall trend with Reynolds number which is broadly similar to that found in steady flow where the drag coefficient decreases considerably with Reynolds number over the approximate range $10^4 < Re < 10^6$.

The flow kinematics of wavy flows past circular cylinders are not yet fully understood. However, recent contributions from research studies such as those of Sarpkaya and his colleagues (e.g., Sarpkaya and Tuter, 1974; Sarpkaya, 1976), have provided significant insight into the understanding of the physical process of planar oscillatory flows. Pearcey (1979) pointed out that one of the major achievements of Sarpkaya's data was to provide convincing information of a significant overlap between the set of viscous flow phenomena involved in periodic oscillatory flow and that for the steady, unidirectional flow. This overlap is reflected in comparing Sarpkaya's test data and those from tests on cylinders in steady unidirectional flow as shown in Fig. 3.2. It can be observed that the curve for

periodic oscillatory flow at a certain Keulegan-Carpenter number* (KC) value has a similar variation with Reynolds number to the classic form for steady unidirectional flow. In particular, the drag coefficients follow in a similar trend from a high "subcritical" plateau to a second and significantly lower "post-critical" plateau, with the "critical" region occurring at a lower value of Reynolds number. This shifting of critical changes is caused by the turbulence swept back from the wake of earlier cycles, and is an inevitable feature of periodic flow.

The overlap in viscous flow phenomena exhibited in both steady and oscillating conditions clearly indicates the dominant part played by separated flow. Discrete vortices and their velocity fields exert a strong influence for oscillatory incident flow which is superficially similar to that for steady unidirectional flow. This overlap also indicates that steady flow values of the drag coefficient are applicable to offshore structures in cases where the diameter of the member is small relative to the amplitude of the fluid particle motion and, therefore, data on drag in steady flow is important in wave force calculations.

However, the differences in flow phenomena between oscillatory and steady flows are extremely important. These qualitative differences between steady and oscillating flow

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*Keulegan-Carpenter number, KC, is defined as $U_m T/D$, where U_m is the maximum fluid particle velocity, T is the period of the oscillatory motion, and D is the cylinder diameter.

results in the quantitative differences in the force coefficient used in the Morison Equation. There is an important distinction between the vortex phenomena observed for steady flow and those likely to occur for oscillatory flow. This is pointed out by Pearcey (1979), who wrote that for steady flow, the shedding of vortices from the two sides of the cylinder in certain flow regimes are due to the unsteady nature of the vortex phenomenon arising from an instability in the wake. For oscillatory incident flow, vortices will be formed, shed and convected backwards and forwards as a consequence of the flow reversals. It is unclear how these processes interact with the processes which are at play in the case of steady incident flow, but almost certainly the interaction will change as Keulegan-Carpenter number changes, and with it the relationship between the reversal period and other periods that characteristically influence the vortex phenomena.

The vortices being convected from what is the wake of one half cycle, past the cylinder to the wake of the next, will interact first with their images in the cylinder, and then with vortices currently being shed. Under the influence of mutually induced velocities, these vortices will, in some cases, be convected with increased velocities past the cylinder, and in other cases, with significant velocities oblique to the main flow. These and other interactions could provide the source for a variety of transverse loads (as a result of asymmetric velocity

and pressure fields) and increased drag (as a result of low pressure fields adjacent to the downstream face and reflected in the increased transport of vorticity.)

In applying test results of laboratory periodic oscillatory flows (such as those of Sarpkaya's data from using the idealised U-tube model) to wave flows, the only significant difference to be noted is the orbital motion of fluid particles in wave flows. Pearcey (1979) suggested that the component of orbital velocity resolved parallel to the axis of the cylinder has a destabilizing effect on the boundary layer about the cylinder. Transition to turbulent flow would therefore be expected to occur at a lower Reynolds number than otherwise, and so would the critical changes from high sub-critical levels of drag coefficient to lower post-critical levels.

3.3 Operating Regimes of the Morison Equation

Hydrodynamic loadings on structures can be conveniently classified into five different types: (1) drag, (2) transverse lift, (3) inertia, (4) diffraction, and (5) reflection. The relative importance of these in a particular case depends on the wave field and the relationship between typical dimensions of the structural body. The relative importance of these can also dictate the applicability of different wave load calculation methods.

In general, drag forces on bluff bodies are related to flow separations caused by viscous effects of the fluid. These drag forces are particularly significant for tubular components of small diameters in waves of large height. Transverse lift forces are the hydrodynamic force components normal to the incident flow and the axis of the structural member as a result of the shedding of vortices or proximity to other members. Inertial loads are related to the pressure gradient associated with the relative acceleration of the ambient fluid, and are more significant for structural components of large sectional dimensions. Diffraction forces are due to scattering of the incident wave by the structure, and are only significant when the sectional dimensions are a substantial fraction of the wave length. Reflection forces are due to the complete reflection of waves on structures whose dimensions are of the same order or larger than the wave length. This reflection force regime is important for coastal engineers designing sea walls and breakwaters, but are generally not significant in the design of offshore structures.

The applicability of the Morison Equation to describe these various types of wave forces depends on the characteristics of wave and structure conditions. An approximate mapping of seven different hydrodynamic operating regimes can be constructed as shown in Fig. 3.3 in terms of dimensionless wave to structure dimension parameters (such as H/D and $\pi D/L$). This exercise can help to better visualize the comparative importance of different

hydrodynamic regimes and the applicability of the Morison Equation in these different regimes.

Consider the horizontal force on a cylindrical structural member of diameter (D) at depth (z) in a linear deep-water wave of height (H) and steepness (H/L = 1/15). It can be shown that the relative importance of the drag (F_D) and inertia forces (F_I) which appear in the Morison Equation can be given by

$$\frac{F_D}{F_I} = \frac{C_D\, e^{(-2\pi z/15)}}{\pi C_M} \cdot \frac{H}{D} \tag{3.3}$$

Under such conditions, the ratio of drag to inertia force is only a function of H/D, for fixed values of C_D, C_M and z. For the purpose of this illustration, C_M has been taken as 1.8 and C_D as 0.6. The ratio F_D/F_I can be computed for any depth and value of H/D. Fig. 3.3(a) was constructed for the simplified case for z= 0 at the free surface.

Regimes I to IV show the relative dominance of drag to inertial force as a function of the ratio of wave height to structural diameter (H/D). The ratio H/D can also be interpreted as a measure of the path length of a near surface orbital fluid particle relative to the structural dimension D. In regime I, the orbit path is long compared to the body diameter, and this represents something approaching a steady flow drag situation where inertia forces can be neglected. In regime IV, the path

length is small compared to the body dimension. Under such conditions, the drag force is small, and the inertia force dominates. Regime II and III covers some of the most important structural types for which design wave forces are computed. These include jackets, legs and main members of offshore rigs and platforms whose H/D values range from about 1 to 40. It is in these regimes that the determination of C_D and C_M is most critical, because both the drag and inertia forces are important.

In Regime V, the wave height H is only a small fraction of the member diameter D. This regime is of almost purely inertia force, with the drag component constituting only about 1 percent or less of the total force.

The approximate threshold for Regime VI, in which diffraction theory methods of analysis are applicable, is when $\pi D/L$ is larger than about 0.6, or when the body diameter is approximately a fifth of the wave length or greater. This threshold was estimated from studies such as those of Chakrabarti and Tam (1973) in identifying the influence of diffraction on total wave forces on large diameter objects. When $\pi D/L$ is larger than about 3, or when the body diameter is larger than the wave length, the wave force will be in the reflection regime. In this Regime VII, neither the Morison Equation nor the diffraction theory is applicable, and the calculation of wave forces is usually based on methods developed by Miche (1944) and Rundgren (1958). The Shore Protection Manual (1976), published the Corps

of Engineers, also has a good description of reflection wave force calculation methods.

A line is drawn in Fig. 3.3 showing the approximate limit of the wave steepness in deep water ($H/L=1/7$). This line may be used to define an upper bound for unbroken wave conditions in which the Morison Equation can be used.

The Keulegan-Carpenter number (KC), which has been defined as U_mT/D, is another useful dimensionless parameter for identifying the approximate loading regimes. The term U_mT, which behaves in a similar manner to H in deep water, is a measure of the path length of an orbital fluid particle. The Keulegan-Carpenter number then may be viewed as comparing the parameter U_mT with the body diameter, and thus functions as a measure of the degree of transience. For sinusoidal, deep water waves, the Keulegan-Carpenter number can be shown to be equal to $(\pi H/D) \cdot e^{(-2\pi z/L)}$. At surface ($z = 0$), the Keulegan-Carpenter number will become $\pi(H/D)$. The influence of the Keulegan-Carpenter number in defining the relative importance of inertia and drag forces is illustrated in Fig. 3.3(a). When the Keulegan-Carpenter number is smaller than 5, the inertia force is predominant, and the total wave force can be approximated by neglecting the drag component. When the Keulegan-Carpenter number is larger than 100, the drag force is predominant, and the total wave force can be approximated by neglecting the inertia component. In between these two extreme conditions, both the inertia and the drag

components are important in applying the Morison Equation.

There is another type of force developed in waves which are often called transverse lift forces. These transverse forces are defined as the component of hydrodynamic forces normal to the undisturbed flow direction and axis of the structural member. This is perhaps an unfortunate name for these forces, as lift implies a vertical upward force. Furthermore, if a structural member is at all compliant, it can more in such a way as to cause these forces to act with a component parallel to the instantaneous flow. Nevertheless, this name is entrenched in the literature, and is therefore adopted in this report. Transverse forces are due to vortices forming and shedding on alternate sides of the immersed member or proximity effects from neighboring members. Transverse lift forces, due to vortex shedding, are significant when the Keulegan-Carpenter number is greater than about 5. In deep water, this is equivalent to a wave height to member diameter (H/D) ratio of about 1.7. The Morison Equation often produces large differences between measured and calculated in-line forces in the range of KC values from 10 to 20, even in controlled laboratory conditions. Sarpkaya (1976a) termed this as the disturbance-sensitive region of vortex formation. This range of KC values is often associated with the occurrence of relatively large lift forces, asymmetry in the in-line forces, and even negative force coefficients. The reason for the asymmetry in the magnitude of the in-line force

and differences between the measured and calculated forces is primarily the fractional or incomplete shedding of vortices and vortex-induced oscillations in the in-line force as explained by Sarpkaya (1976a). For larger values of KC, predictions of wave force by the Morison Equation are usually in good agreement with measured forces.

Figs. 3.3(b) and 3.3(c) plot the wave loading regimes at depths of 150 ft. and 300 ft. below surface for a wave height of 30 ft. These figures show the effect of the exponential decay with depth of the ambient wave particle velocity and acceleration and its effect on redefining loading regimes. In general, with greater depth, the orbit length is reduced, and the inertia force becomes dominant for a wider range of H/D. However, since the inertia and drag forces also decay exponentially with depth, the wave forces at depths greater than half the wave length are usually insignificant.

A numerical mapping similar to that shown in Figs. 3.3(a), 3.3(b) and 3.3(c), showing the comparative importance of the drag, inertia and diffraction in various regimes of structural and wave dimensions has been constructed by Hogben* (1976) as shown in Fig. 3.4. The relation of different structural types and sizes with wave heights and water depths in the loading regime figures is also shown. Fig. 3.4 shows that gravity-type

*Hogben (1976), in constructing his original figure, misinterpreted the division lines which showed the drag to inertia force ratios (F_D/F_I) equal to 0.9 and 0.1 as the 90% and 10% drag division lines. These corrections have been made in adapting Fig. 3.4 from Hogben's work.

structures that commonly have a large base may experience some diffraction forces even in extreme wave conditions. Other components, such as the towers supporting the deck of a platform, may generally lie entirely in the inertial regime during severe conditions. The loads on very small diameter components, such as braces and conductor tubes, may be drag-dominated. In practice, overlapping of the loading regimes should be considered, and it may be necessary to use diffraction theory methods in combination with the Morison Equation, even when there is no significant wave scattering, to determine the inertial forces on complex shapes and account for interaction between neighboring numbers.

Jacket structures and jack-up platforms are of tubular construction, with structural member diameters generally lying in the drag-dominant regime in the more severe conditions. In deeper waters, the structural leg members may, however, be large enough to incur significant inertia forces. For normal conditions, smaller wave heights can also induce inertia forces which may be important for the consideration of dynamic response and fatigue stresses.

However, it is important to point out that these mappings of loading regimes are obtained by assuming some appropriate sets of specific values of wave conditions and wave theory, and can be regarded only as general guidance.

3.4 Wave Force Coefficients

In the regions where the Morison Equation is applicable, force can be computed only if the relevant drag and inertia coefficients are known for the specific structural configurations and design sea states concerned. The determination of drag and inertia coefficients has been a key topic in wave force research since the Morison Equation was introduced in the 1950's. Very considerable resources in terms of people, talent and facilities are still involved in this task. With some of the significant research results recently available, investigators are perhaps just beginning to be able to reduce and explain some of the conflicting experimental data and uncertainties about the choice of force coefficient in values.

A critical review of the published data on the drag and inertia coefficients, C_D and C_M, has been undertaken by the British Ship Research Association (BSRA, 1976). A tabulated documentation of results from the BSRA investigation is shown in Appendix A. A summary of most of the prominent laboratory and field tests on the study of wave force coefficients was provided with the values of the key parameters, associated test conditions, as well as their reliability and application to practical structures. Results from some of the more recent full-scale tests (e.g., Exxon Ocean Test Structure, Conoco Test Structure) have been added to the list. Hogben, et al., (1977) provide suggested values of C_D and C_M in relation to the

corresponding values of Keulegan-Carpenter number (KC) and Reynolds number (Re), based on the BSRA study.

The Keulegan-Carpenter number and the Reynolds number are considered to be the best dimensionless numbers for parameterizing the values of force coefficients. Experiments in the controlled laboratory conditions of simple harmonic planar flow in a U tube apparatus led Sarpkaya (1976) to the conclusion that the inertia and drag coefficients are definitely functions of the Reynolds number and the Keulegan-Carpenter number. To illustrate this, the recommended values of the drag and inertia coefficients given by Hogben, et al. are shown in Fig. 3.5 in terms of different regimes governed by conditions specified by the Keulegan-Carpenter number and the Reynolds number. The intermediate boundaries of these three regimes are not precise, and are chosen for convenience in discussion and classification of the wave force coefficients.

The suggested values of the drag and inertia coefficients summarized in Fig. 3.5 applies only to isolated smooth vertical cylinders. No allowance has been made for the interactive effects such as roughness, different cylinder orientations, slamming, interference from other members and currents, etc. The drag and inertia coefficient values suggested have been determined solely on the basis of the references cited, and they should be used strictly for the same set of conditions defined.

In order to guide the selection of force coefficients and for different design conditions, six different force coefficient regimes are delineated in Fig. 3.5 according to their relations to the drag and inertia coefficients.

Force Coefficient Regime 1

Regime 1 represents the subcritical Reynolds number regime where drag force is significant. Considerable amounts of scale model data are available for this regime. In this regime, the recommended wave force coefficient values are those suggested by Keulegan and Carpenter (1958) shown in Fig. 3.6. These results were obtained in one-dimensional harmonic flows, as were the similar results of Sarpkaya and Tuter (1974). Susbielles, et al. (1971) used the values reproduced in Fig. 3.6 to calculate local wave forces on a vertical pile, and obtained agreement with measured forces to within 10 percent. The errors and uncertainties in this regime are larger around the critical conditions when $10 < KC < 20$ where the flow is affected by fractional or incomplete vortex shedding, and becomes highly complex.

Force Coefficient Regimes 2 and 3

Regimes 2 and 3 cover the critical range of the Reynolds number. In these regimes, published data show considerable scatter. Hogben and his co-workers were not able to specify any single value for the drag coefficient. Instead, a range of drag coefficient decreasing from 1.2 to 0.6 was suggested as the

Reynolds number increases within the regime from about 5×10^4 to 5×10^5. This recommendation was largely based on the results of Wave Force Projects I and II, and the works of Rance (1969), Sarpkaya (1976), and Wiegel (1957). Results recently reported by Heideman, et al. (1979) on the Ocean Test Structure also show a similar range of variation for drag coefficient for smooth members. Heideman, et al. also found that the degree of scattering of drag coefficient decreases as the Keulegan-Carpenter number becomes larger and levels off to a value of 0.68 when the Keulegan-Carpenter number reaches about 40.

In these regimes, the suggested design value for the inertia coefficient is 1.5, based on the data presented by Aagaard and Dean (1969), Rance (1969) and Sarpkaya (1976). Results from the Ocean Test Structure reported by Heideman, et al. (1979) also suggest a similar mean value for the inertia coefficient. The accuracy of the inertia coefficient at high Keulegan-Carpenter numbers becomes less important because drag force then becomes increasingly dominant. However, the reliability in total and local wave forces calculated using the values suggested in Regimes 2 and 3 cannot be assessed rigorously, and in general, errors of the order of 100 percent or more are possible.

Force Coefficient Regime 4

This regime represents the post-critical Reynolds number and Keulegan-Carpenter number conditions where the drag force is significant. The suggested drag coefficient for design in this

regime is 0.6, based on results reported on the Wave Force Projects I and II (Aagaard and Dean, 1969; Evans, 1969; Hudspeth, et al. 1974; Wheeler, 1969), the Bass Straits experiment reported by Kim and Hibbard (1975) and the pulsating water channel experiments reported by Rance (1969). At high Keulegan-Carpenter numbers, (KC approximately above 100), the fluid motion around the cylinder is quasi-steady and so, at post-critical Reynolds numbers, drag coefficients are expected to be close to those of steady flow, which are in the range of about 0.6-0.7. The inertia coefficient value suggested for this regime is 1.5, based on the same sources as the drag coefficient. However, at high Keulegan-Carpenter numbers, the inertia coefficient is of little significance because drag is then dominant.

Analysis of the Wave Force Projects I and II and Ocean Test Structure data (Hudspeth, 1974; Haring, et al. 1979) reported that the estimation of the total wave forces, integrated over the total depth of a member, is far more reliable than that of the local forces for data within this regime. Examples are given in these references in which local force maxima, calculated using average values of coefficients, differ by more than 50 percent from the measured values. However, for the integrated forces along the member, the agreement is much better, and often within 10 percent. Agreement is also good between measured total forces and calculated total forces at various points within a wave cycle, using constant inertia and drag coefficients.

Hogben, et al. (1977), suggested that for this force coefficient regime, errors of the order of 20 percent are considered to be conservative for the case of the total horizontal force, and errors of 50 percent or more are possible for local forces. A study of wave force measurement correlations in this regime by Bea and Lai (1978) found a drag coefficient of 0.6 gave an unbiased estimate of total wave forces, and developed a coefficient of variation of 30 percent.

Force Coefficient Regime 5

Regime 5 represents the critical range of the Keulegan-Carpenter number, and the post-critical range of the Reynolds number. This is a disturbance-sensitive regime where the flow is complicated by the fractional or incomplete shedding of vortices. In this regime, the situation is far less certain than it is in Regime 4 because of lack of data. Hogben, et al., (1977), suggested a drag coefficient of 0.6, and an inertia coefficient of 1.5 for design in this regime, but said that the reliability is considerably less than it is for a higher Keulegan-Carpenter number condition. Results from an important full-scale test were recently reported by Ohmart and Gratz (1979) performed in the Gulf of Mexico. A large part of the data lies in this regime. A higher mean drag coefficient of 0.7 was recommended.

Force Coefficient Regime 6

Regime 6 covers the inertia dominant regime where the Keulegan-Carpenter number is less than about 5. For large-diameter cylinders when the Keulegan-Carpenter number is low and diffraction effects are negligible ($D/L \lesssim 0.6$ as shown in Fig. 3.3), the regime is dominated by inertia forces. In this case, the theoretical potential flow value of 2.0 for the inertia coefficient is suggested for design purposes because of negligible drag force. The largest published difference between measured and calculated forces, using this value of inertia coefficient, is about 20 percent as reported by Hogben, et al. (1977).

For structures whose dimensions are large compared to wave length ($D/L \gtrsim 0.6$ as shown in Fig. 3.4), the Morison Equation method is not applicable as the assumption of having constant velocity and acceleration values across the dimensions of the structures is not valid. In this case, the diffraction theory as reported by Chakrabarti and Tam (1973); Garrison, et al. (1974); and Hogben and Standing (1975) can be used.

The above suggested design values of drag and inertia coefficients are based on critical reviews of available published research works. As the literature on wave force studies is expanding rapidly, a continuous effort should be maintained in updating these design values, especially in regimes where the reliability level of presently suggested values are low.

3.5 Wave Kinematics

Water particle velocities (u) and accelerations ($\dot{u}$), play a very essential role in the process of computing wave forces on offshore structures using the Morison Equation formulation. A large number of wave theories have been developed in an attempt to describe the complex motion of ocean waves. The following is a list of the primary wave theories being used:

1. Airy Wave Theory
2. Stokes Fifth Order
3. Solitary Wave Theory
4. Modified Solitary Wave Theory
5. Chappelear Theory
6. Stream Function Theory
7. Extended Velocity Potential Theory

Each theory, be it linear or nonlinear, analytical or numerical, has its own limitations and ranges of applicability. Much work has been done in developing design guidelines for selecting the appropriate wave theory for specific site conditions. Earlier studies by Keulegan (1950) have shown that in shallow water, wave conditions are nearly independent of wave length, and the two important parameters are water depth and ratio of wave height to water depth (H/h). In deep water, he reported that the two important parameters are wave length and wave steepness (ratio of wave height to wave length, H/L).

A study of the validities of different wave theories was conducted by Dean and LeMehaute' (1970). Their results, showing the approximate regions of validity of different wave theories in relation to two parameters (H/T^2 and h/T^2) are shown in Fig 3.7. However, there are no sharp lines dividing the applicable regions. Designers should allow some overlap when selecting wave theories from guidelines such as Fig. 3.7. In general, review of studies of the relative validity of wave theories tends to show general agreement in the applicability of Cnoidal Theory for shallow water waves of low steepness, and Stokes higher order theories for steep waves in deep water. These studies differ in regions assigned to Airy Linear theory. The Stream Function Theory is most internally consistent over a wide range of conditions. However, waves of low steepness in intermediate and deep water appear to be equally well represented by both Stream Function and Airy Theory. However, substantial developments in the applications of Stream Function Theory tend to predict a wider usage of this wave theory to offshore design problems (Dean, 1972).

The determination of force coefficients from laboratory and field wave force measurements also depend on the kinematics inferred from wave theories if the direct measurements of wave orbital currents are not available. Rather different values of drag and inertia coefficients can be required to match the same set of wave force data when different wave theories are used.

The analysis of the Wave Force Project II data provides an example. Evans (1969) reported a drag coefficient of 0.5 and an inertia coefficient of 1.5 by using the Stokes Fifth Order Theory. Wheeler (1969) found a drag coefficient of 0.6 and an inertia coefficient of 1.2 by using the Linear Filtering Method, while Aagaard and Dean (1969) found a drag coefficient of 0.55 and an intertia coefficient of 1.33 by using the Stream Function Theory. In selecting recommended force coefficients from design guidelines such as Fig. 3.5, or from published research, designers should be aware of the interdependence of force coefficients and wave kinematics. Design values should be chosen so that they represent the same conditions from which they were developed.

3.6 Validity of the Morison Equation

The Morison Equation, as discussed in Section 2 of this report, has its origins in the work of Stokes (1851) and, strictly speaking, pertains only to the components of force that are in line with a one-dimensional unsteady flow. The Morison Equation is generally regarded as a semi-intuitive engineering expression which is used to approximate the force exerted on a body in a viscous fluid under unsteady flow conditions. In general, the force experienced by a bluff body at a given time depends on the entire history of its accelerations as well as the instantaneous velocity and acceleration. Thus, the drag coefficient in unsteady flow is not equal to that developed at a

corresponding instantaneous velocity in steady flow. Moreover, the inertia coefficient is not equal to that found for unseparated potential flow. The Morison Equation neglects the dependence of the force upon the time history of the flow. Instead, the force at any instant is related to the instantaneous fluid particle velocity and acceleration as well as a set of force coefficients which are taken as constant throughout the wave cycle.

However, numerous researchers both in laboratory and field conditions, have indicated that the Morison Equation, used in the appropriate ranges of fluid-structure operating regimes, is a good force predictor given the values of the fluid particle kinematics and the empirical force coefficients. In particular, Sarpkaya (1976a) employed the Morison Equation to determine drag and inertia coefficients from an oscillating U-tube experiments using, as parameters, the Reynolds number and the Keulegan-Carpenter number. Sarpkaya found that, except over the range of the Keulegan-Carpenter numbers (about 10 to 20), for which the wake effects are rather erratic, the Morison Equation represents the oscillating forces on the cylinder with surprising accuracy. Sarpkaya's results are of special interest to the discussion of the suitability of the Morison Equation as a force predictor because kinematics in his experiments are known rather precisely.

The major difficulty in applying the Morison Equation is the selection of the appropriate force coefficients from the widely scattered data in literature. This generally requires good judgment and experience in selecting and/or modifying values of the coefficients to fit the particular problem. The major factors that have caused the scatter in force coefficient data are:

1. The inaccurate determination of the fluid particle kinematics in many laboratory experiments.
2. The non-uniform techniques in deriving force coefficients from force measurement data.
3. Experimental error.
4. Inexact description of the complex flow.
5. Incomplete parameterization of the force coefficients.

Each of the above are explained in detail in the following paragraphs.

Fluid Particle Kinematics

As discussed in Section 3.4, the determinations of force coefficients and fluid-particle kinematics are interrelated. Due to the difficulty of accurately measuring ambient wave kinematics in experimental wave force measurement programs, most of the studies required that the kinematics used in the correlation of measured forces with the Morison Equation be established through the use of some suitable wave theory. As a result, different wave theories will, in general, produce different pairs of force

coefficients for the same data. In field measurements, the situation is further complicated by the presence of ocean currents and the three-dimensionality of sea waves which would greatly distort the values of local kinematics from that represented by a two-dimensional wave theory. For experimental conditions where the kinematics are accurately known, such as Sarpkaya's U-tube experiments, the scatter of force coefficient data is reduced.

Experimental Methods

Different techniques have been used by researchers in deriving force coefficients from force measurement data and are expected to produce different results (Ramberg and Niedzwecki, 1979). The technique originally employed by Morison, et al. to obtain C_M and C_D was to set the measured force equal to either the drag or intertia component when the other was theoretically zero. Keulegan and Carpenter (1958) later separated the measured force into its Fourier components whose amplitudes could then be used to determine the force coefficients. With this method, a residual or remainder force, not accounted for by the original Morison technique, was identified both in amplitude and frequency. Another technique calls for fitting the Morison Equation to the measured force record in a least-square error sense with C_M and C_D as the curve fit parameter. Each of the above methods is well-known and widely used. However, the different methods will, in general, produce different pairs of

coefficients for the same force record. Even for one-dimensional harmonic flow conditions such as Sarpkaya's U-tube experiments, a 4 percent difference in the drag coefficient was obtained by comparing both the Fourier and the integral least-square method (Sarpkaya, 1976a).

Experimental Error

There are a number of possible situations which could result in experimental errors that could affect the force coefficients. Errors could result from measurement of the sea surface, calibration of the force transducers, error in measuring the fluid particle kinematics, etc. One possibility of experimental error is simply instrumentation sensitivity and the low magnitudes of forces and other variables during periods of small waves. Dean (1976) showed that depending on the wave and cylinder characteristics, data can be well- or poorly-conditioned for resolving drag or inertia coefficients, and it is believed that much of the scatter in the reported coefficients may be from data that were poorly conditioned for resolving them. In general, if the drag forces tend to dominate, then the data are better conditioned for determining the drag coefficient, and the inertia coefficient would tend to be contaminated by the errors of various sources noted earlier. Conversely, if the inertia force component tends to dominate, then reasonable resolution in the inertia coefficient can be expected along with contamination of the calculated drag coefficient. If the maximum drag and inertia

coefficients are of the same order of magnitude, then reasonable resolution in both of these coefficients can be expected if the general quality of the data is good.

Inexact Description of Complex Flow

The inexact description of the fluid-structure interaction by the Morison Equation itself contributes a certain amount of uncertainty in determining the force coefficients. One source of uncertainty is the existence of vortex-generated lift or transverse force which is not included in simple forms of the Morison Equation. In particular, the previously-described disturbance-sensitive region of vortex formation near the range of Keulegan-Carpenter number from about 10 to 20, is often associated with large lift forces and asymmetry in the in-line forces.

There are additional hydrodynamic complexities encountered in wave flows that are not sufficiently described by the Morison Equation, but add to the uncertainty in deriving force coefficients. The eccentricity of the water particle orbits and the orientatin of the structural cylinder with respect to the orbits can cause asymmetric flow about the cylinder axis, or that the wake is not necessarily always sweeping back and forth over the cylinder (Pearcey, 1979). Another complexity is represented by the flow not being always uniform along the span. This variation of flow along the span can introduce three-dimensional effects in a number of ways that influence the force

coefficients. The instantaneous velocities and accelerations can have an axial variation which can alter the flow forces away from the distribution predicted using one-dimensional flow results. The other three-dimensional effect can arise from the wake which may be swept back over or near one segment of the cylinder after being generated at another segment under different flow conditions.

Another source of uncertainty concerns the theoretical influence of convective acceleration terms on the inertia force. The inertia force as applied to the Morison Equation is usually taken as proportional either to the local (temporal) fluid acceleration or to the total (local plus convective) fluid acceleration at a point in nonlinear waves. Even though these may differ significantly from each other in typical design waves, no formal justification exists for adopting one or the other. Isaacson (1979) derived a complete expression for the inertia force acting on a body in an unsteady nonuniform flow of an inviscid fluid. He found that the force depends on convective acceleration terms, although the force is not necessarily proportional to the total (i.e., local plus convective) acceleration at a point. However, he also found that for most wave conditions, these calculated forces are generally less than forces taken as proportional to the local fluid acceleration.

In addition to experiment difficulties arising from "hard to control" flow patterns described above, the net effect of stochastic flow elements must be kept in mind. In theory, simple wave motion can be irrotational. However, when an obstruction, such as a structural member, is introduced into such flow, fluid shear, vortices, and turbulence are developed. Furthermore, the real environment of offshore structures is virtually always turbulent because of non-ideal waves or the turbulence of ocean currents. Even carefully controlled laboratory experiments using such devices as oscillating water tunnels must develop turbulence as a consequence of fluid shear against the tunnel walls. The turbulence can introduce scatter in the experimental results when the turbulence scales are large (e.g., prototype scale in the ocean). Furthermore, pre-existing turbulence influences the boundary layer development on the structural member, the degree to which the flow is deflected as it moves around the member, and the triggering of wake vortices. The oscillation of the flow can cause all of this to be washed back over the member to influence the next cycle.

At present, the effects of turbulence must be reduced through statistical treatment of experimental data because so little is known about the nature of ocean turbulence. However, future analytical and experimental work must be designed to more carefully evaluate the role of turbulence in relating wave kinematics to wave forces.

Incomplete Parameterization of the Force Coefficients

Early researchers attempted to develop relationships between the differing values of the force coefficients used in the Morison Equation and the Reynolds number parameter. Although some of the variation of the coefficients can be accounted for through the use of the Reynolds number, it became clear that the relatively clear relationship which can be obtained in steady flow cannot be replicated in oscillating flow. The pattern of scatter associated with experimental data on wave forces from oscillating flow has been somewhat more controlled by more recent work which includes both the Keulegan-Carpenter and the Reynolds numbers. Work presently underway suggests that other dimensionless parameters can be determined to further order the results of experiments and lead toward yet more precise methods for evaluating the force coefficients. This work is badly needed in light of the large uncertainties associated with the choice of force coefficient values in many important flow regimes.

4.0 EXTENSIONS OF THE MORISON EQUATION

As discussed in the previous chapters, the original Morison Equation and the recommended values of force coefficients were developed for, and limited to, the horizontal wave forces on smooth, vertical, isolated, circular cylinders that pierce the free surface. Special considerations and modifications have to be made on the applications of this equation to the not-so-ideal situations where a structural member may be: inclined; of non-cylindrical shape; fouled by marine growth; affected by flow conditions from adjacent objects; compliant or in motion due to compliance of the general structure; acted on by multi-directional seas, impacted by surface wave slamming, and other factors. The extended applications of the Morison Equation are discussed in the following sections.

4.1 Inclined Members

In the original Morison Equation (Equation 2.1), the velocity and acceleration components (u, $\dot{u}$) are defined to be at right angles to the vertical member axis. The vertical or the tangential components are ignored in the force evaluation. Since the introduction of the original equation, several modifications and methods of analysis have been developed to extend its usefulness. A limited number of approaches to the problem have been proposed by Borgman (1958), Chakrabarti, et al. (1975), and others, for applying the Morison Equation to inclined members, such as the cross-bracings of a fixed offshore platform. A

summary of the different approaches was reported by Wade and Dwyer (1976). The assumptions involved in these approaches are one of the following:

1. The drag and inertia force resultants acting on a projected area of the inclined cylinder are to be considered.
2. Only the components of force acting normal to an inclined member produce loads.
3. Only the components of velocities and accelerations normal to the inclined member produce loads.
4. Resultant water particle velocities and accelerations are taken to act perpendicular to the longitudinal axis of an inclined member to a yaw angle of 60 degrees.

The first method assumes that the drag and inertia force resultants act on a projected area of the cylinder that is inclined about a normal to the sea bottom. The velocity and acceleration vectors act on an elliptical cross-section whose major axis is always parallel to the instantaneous direction of flow. The selection of the drag and inertia coefficients for this case provides an additional degree of uncertainty since the C_D and C_M values for elliptical cross-sections are expected to be quite different from that of circular cross-sections.

In the second method, the resultant drag and inertia forces are resolved into normal and tangential components with respect to the longitudinal axis of the inclined cylinder. The normal

components of forces are retained, while the tangential forces are ignored. The skin friction effect on the structure are assumed to be minimal. In this case, the total force has drag and inertia force components that are not coplanar, but both act normal to the longitudinal axis of the member.

The third method retains the normal components of water particle velocity and acceleration and discards the tangential kinematic components. The total force has drag and inertia forces that act normal to the longitudinal axis of the member. In general, the drag and inertia vectors will not be coplanar. Also of note is that the drag force in this case will have a cosine squared term. It would be expected that this method will give significantly less force on a drag-dominated structure than those predicted by the first two methods.

The fourth method is the most conservative method considered. This method assumes that resultant water particle velocities and accelerations always act perpendicular to the longitudinal axis of the inclined member to a yaw angle of 60 degrees. Yaw angles are formed by the included angle between the normal to the member's longitudinal axis and the resultant velocity or acceleration vectors. The resultant kinematic vectors, which are rarely normal to a member's longitudinal axis, are rotated up to 60 degrees without changing the magnitude of the vector and then applied to the entire length of the inclined member.

Wade and Dwyer (1976) made a comparison of the four methods in computing wave forces on jacket-type offshore structures. They report that variations of base shears and overturning moments on the structures, calculated by the four different methods discussed above, can be as large as 22 percent. Nevertheless, all the methods are procedures generally used by industry at present. Conclusive calibrations with test data on these methods have not been made. Additional research work is required in order to establish a uniform criteria for determining wave loads on inclined members.

Studies on wave force coefficients associated with inclined members are also very limited. It is suggested by Hogben, et al. (1977) that the values of the drag and inertia coefficients recommended in Fig. 3.5 should be used, with Reynolds number and Keulegan-Carpenter number evaluated from the cylinder diameter and the maximum normal velocity component. The degree of reliability cannot be assessed until more conclusive research on this topic is available.

4.2 Other Structural Shapes

The Morison Equation was originally developed for a circular cylindrical member, which is by far the most widely used structural shape in constructing offshore structures. However, in some special instances, wave forces on other structural shapes may have to be determined. Limited studies were published on the application of the Morison Equation on structural shapes other

than circular cylinders. Values of drag coefficient as a function of Reynolds' number have been given for some two-dimensional prismatic shapes in steady flow by Delany and Sorenson (1953) and Hoerner (1965). Values of the drag coefficient tend to remain constant over all ranges of the Reynolds number for shapes with geometric discontinuities, but as the shapes become smoother, the variation of the drag coefficient with the Reynolds number tends to be more like that for circular cylinders. A recent experimental study was reported by Bearman, Graham and Singh (1978) on the measurements of force coefficients in planar oscillatory flows. Structural shapes including flat plate, square, diamond and circular cylinders were tested in the subcritical Reynolds number regime over the Keulegan-Carpenter number range from 3 to 70. Their results are shown in Fig. 4.1 and 4.2, where the drag and inertia coefficient were plotted against the Keulegan-Carpenter number for the four body shapes.

In general, the flat plate, square and diamond shapes all produce larger drag coefficient values than circular cylinders at high Keulegan-Carpenter number ranges. This again implies that the circular cylinder is a more efficient structural element in viscous wavy flows. Beyond a Keulegan-Carpenter number of about 10 to 15, the curves for the flat plate, diamond, square and circular cylinders are remarkably similar. At low Keulegan-Carpenter numbers, the inertia coefficients approach very close to their potential flow values. The flat plate, circular

cylinder and diamond cylinder all show a minimum value in inertia coefficient between a Keulegan-Carpenter number of about 15 to 20. The square section cylinder has a different behavior and shows evidence of being very sensitive to the turbulence in the wake flow swept back past the body.

Grace and Casciano (1969) have published a study of wave forces on spheres. The force coefficients suggested are $C_D = 0.7$ and $C_M = 1.2$. The measured and calculated wave forces agreed, in general, to within about 25 percent. Wave force coefficients for a sphere have also been given as a function of Keulegan-Carpenter number from work by Sarpkaya and Tuter (1974) in planar oscillatory flows. At high Reynolds numbers, values of drag coefficients are likely to be smaller.

4.3 Effects of Surface Roughness

Recommended values of drag and inertia coefficients shown in Fig. 3.5 pertain to circular cylinders with a smooth surface. However, offshore structures in the real sea environment are usually fouled by accumulations of marine growth or due to corrosion. Such effects may not only increase the size of a structural member significantly, but also produce a surface that is very hydrodynamically rough. In computing wave loads on marine-fouled structural members, the designer has to estimate: (a) the thickness of growth, and hence the increase in diameter and volume; and (b) the effective roughness height k_r and hence the relative roughness k_r/D for determining the effect of

roughness on the force coefficients.

Roughness generally increases rates of boundary layer growth, as well as the magnitude of the skin friction. A normal method to account for fouling is to increase the value of the drag coefficient. The change in drag coefficient has been measured as a function of roughness relative to cylinder diameter k_r/D. Measurements on the effect of relative roughness height on the post-critical level of drag coefficient in uniform incident flow have been reported by Achenbach (1971), Wong (1977) and Miller (1977). Their results are compiled and shown in Fig. 4.3, adopted from Hogben, et al.(1977). The drag coefficient is shown to increase with increasing relative roughness. The curve levels out at about 60 percent above its smooth value for a range of roughness height, and then increases again.

Effects of various degrees of relative roughness on drag and inertia coefficients in the critical Reynolds number and Keulegan-Carpenter number regimes were measured by Sarpkaya (1976) in planar oscillatory flow (see Figs. 4.4 and 4.5). In general, the transition from critical to post-critical region (where the drag coefficient falls steeply with increasing Reynolds number) occurs progressively earlier as roughness k_r/D increases. The minimum drag coefficient also increases with increase in roughness and the drag coefficient at high Reynolds number is higher than it is for smooth cylinders.

Direct comparisons of the force on a rough cylinder with that on a smooth cylinder in laboratory waves were conducted by Matten (1977). In his experiments, the two cylinders were mounted side by side. They were acted on by the same waves, but were far enough apart in a lateral direction to avoid spurious interference. Matten provided direct evidence that roughness produces large increases of loading in waves (see Fig. 4.6), sometimes as much as 50 percent above the loading on smooth cylinders. Comparisons of C_D values on a smooth cylinder and a barnacle-encrusted cylinder in real sea conditions were also reported by Heideman, et al. (1979) in the Ocean Test Structure Experiment. Flow conditions represent a range of Keulegan-Carpenter numbers up to 60 and a range of Reynolds numbers from 2×10^5 to 6×10^5. The drag coefficient was found to increase from 0.68 to 1.0 in the asymptotic limit of high Keulegan-Carpenter number region (shown in Fig. 4.7). This demonstrates an almost 50 percent increase in the drag force on a fouled cylinder over the corresponding value for a smooth cylinder.

From the above research works, it is apparent that the effect of roughness and fouling on wave forces can be very significant. The increased drag coefficient is applied to a larger-than-original cylinder due to the fouling. This further amplifies the increase in the drag force on a fouled structural member. However, there is still a large degree of uncertainty

on the exact effect of surface roughness due to the scarcity of data and the limited coverage of flow regimes by existing results.

4.4 Interference Effects Due to Neighboring Objects

The Morison Equation and the force coefficient were developed originally for single cylindrical members. The flow over groups of cylinders in which the members are not far apart is different from the flow past isolated cylinders. Also, the fluid forces on a structure are not, in general, equal to the sum of the forces which would be exerted on its constituent members in isolation. This effect of shielding (or proximity effects) include: conditions near the joints of lattice structures; conductor groups or marine risers, where a relatively large number of pipes are bundled together; or situations in which relatively small bracing members lie in the diffraction field of a large adjoining member.

Reviews of this subject on interference effects have been given by Sarpkaya (1978b), Hogben, et al. (1977), and Zdravkovich (1977). Common practice in steady flow calculations is to allow for shielding (by upstream cylinders) when cylinders are within a certain critical spacing of each other and thus inducing certain mutual interference effects. Hoerner (1965) reported that for two cylinders in a tandem arrangement (one cylinder behind the other), the critical spacing relative to cylinder diameter, S_c/D, is about 4. When the spacing is less than the critical spacing,

the upstream cylinder takes the major forces, and the total drag for the group is smaller than the sum of the drag forces acting on each cylinder in isolation. The reduction of the drag coefficient for the downstream cylinder is due to the effect of wake flow induced by the upstream member on the circumferential pressure distribution. Hoerner (1965) also reported that two cylinders in a side-by-side arrangement will exhibit disturbances in the flow and measured forces for spacing ratios smaller than a critical value of $S_c/D \simeq 2$. This results from the mutual interference of the vortices on the adjacent sides of the vortex streets.

Additional work with tube arrays in steady flow has been reported by Laird, et al. (1967); Chen (1972); Arita, et al. (1973); Dalton and Szabo (1976); and Pearcey (1975). In a test on 3 x 3 arrays of circular cylinders with three diameter spacings, small variations of the drag coefficient were found in steady flow (Pearcey, 1975). It was also found that when the flow direction is in line with the rows of tubes, there will be a reduction in the drag coefficient for the downstream members, but for certain other orientations, the interference effects may lead to increases in drag coefficient for some of the members. Although the excursion between the maximum and minimum values could be significant for some of the individual members, neither the maximum drag for any member, nor the average for all members is very different from that of a single tube. The variations in

the average drag with change in orientation are also relatively small. Some of the results of Pearcey (1975) are shown in Figs. 4.8 and 4.9.

Data on the interaction between drag and inertia coefficients for cylinder groups in waves is very limited. The inertia coefficient for a group of cylinders in inviscid unseparated flow can be obtained through the use of potential flow theory (e.g., Dalton and Helfinstine, 1971; Yamamoto, 1976; Chakrabarti, 1978). However, these studies do not deal with the effects of separation and vortex shedding, so that the results are more appropriate for determining wave forces on large bodies, or at low Keulegan-Carpenter number, rather than to the evaluation of the inertial component of the force in the drag/inertia dominated regime.

Bushnell (1977) tried to study the interference effects on the drag and transverse forces acting on a two-cylinder configuration through the use of a pulsating water tunnel. His results showed that the presence of neighboring cylinders significantly affects the forces on an individual cylinder of an array, and the interference effect increases with increasing relative flow displacement. The maximum drag force on shielded cylinders was reduced relative to an exposed cylinder by up to 50 percent. Bushnell suggested that a design using a high Reynolds number single-cylinder drag coefficient applied throughout the array would have an extra margin of safety against maximum drag

loading due to interference effects. The transverse forces in the case of cylinder groups can be very significant due to mutual interferences and may exhibit very complex dynamic behavior.

Sarpkaya (1978b) conducted a laboratory study of two arrays consisting of 15 outer pipes and one central pipe subjected to harmonically oscillatory flow. He found that the drag and inertia coefficient are independent of Reynolds number and reach their asymptotic values at relatively small values of Keulegan-Carpenter number. The inertia coefficient was shown to be considerably larger than that predicted by the potential theory, and it appears that some fluid mass was entrapped within the bundle as a consequence of the solidification of tube configuration.

It is difficult to generalize or predict the interference effects in wave flows on the basis of relatively idealized situations before more reliable data are available. However, Hogben,et al. (1977) suggested two basic ground rules for designers concerning drag forces on grouped structural members:

1. If the cylinders are further apart than half the wave height, the water is reasonably deep and with no current, the drag coefficient is probably unchanged from its value for an isolated cylinder because the wake of any cylinder can, at most, be of the order of H/2 long.

2. If the Keulegan-Carpenter number is large, then the steady flow drag coefficient values may be used. If the cylinder under consideration is shielded for both fore and aft flow directions and is sufficiently close to those shielding it, steady flow shielding factors may tentatively be assumed, but only for restricted flow directions.

In general, the application of shielding factors for wave flows has not been quantified.

4.5 Transverse Lift Forces

As described in Section 3 of this report, transverse forces on a structural member are defined as the component of hydrodynamic force normal to the undisturbed flow direction and the axis of the member due to vortex effects. When the transverse force is in the upward direction, it is generally called "lift". The onset of established periodic lateral forces on cylinders was deduced by Keulegan and Carpenter (1958). They proposed that the parameter $U_m T/D$ should be adopted to indicate whether or not the flow could establish periodic wake motion, and attached the value $U_m T/D \gtrsim 15$ as the threshold for lift forces. This transverse or lift force per unit length, F_L, is formulated in a form analogous to the drag force, i.e.,

$$F_L = C_L \, 1/2 \, \rho \, D \, u^2 \qquad (4.1)$$

where C_L is the lift coefficient.

The nature of these transverse forces is not well understood for oscillatory flows. The lift coefficient C_L will have a time-averaged value of zero if flow and cylinder are uniform and symmetric. However, periodic transverse pressure fluctuations associated with the formation of vortex motion in the wake can occur, then C_L will be defined by the r.m.s. values of the force variations.

The frequency of these transverse forces has been related to the Strouhal number (S_t) and Reynolds number (Re) for steady flow. The Strouhal number is defined as Df_n/u, where D is the member diameter, f_n is the shedding frequencies of the vortices, and u is the fluid particle velocity. Laird (1962), in an experimental study on flexible cylinders, demonstrated the importance of transverse forces when the frequencies of the structure and transverse forces are in a lock-in or vortex synchronization situation. Laird found that if the eddy shedding period was near the natural period of the cylinder, transverse forces could develop magnitudes over four times the magnitude of drag force calculated for corresponding uniform steady flow at the same fluid flow velocity. This nonlinear mechanism accounting for the increase in lift forces had been explained by Dean and Harleman (1966):

"The axial length of a shed vortex (which causes the lift force) is more or less proportional to the cylinder diameter in cases where the transverse cylinder oscillations are small. For these conditions, then, there is little likelihood that a vortex will be shed simultaneously along the entire cylinder length. If the transverse cylinder oscillations are on the order of a cylinder diameter, however, the eddy and cylinder systems become coupled and the cylinder motion acts as a "mechanism" to trigger the simultaneous shedding of a vortex along the entire length of the piling, thereby resulting in extremely large lift forces. In addition, for fairly large cylinder oscillations the wake width is increased, which increases the strength of the shed vortices."

The situations for structural members under unsteady oscillatory flow are not well understood. However, similar magnification of transverse forces can be expected as in the case of the oscillations of long piles and strumming of cable-stayed structures in the ocean under similar conditions.

Studies of transverse lift force in waves have been very limited. Sarpkaya (1976b) conducted a series of laboratory studies on transverse forces in planar oscillatory flow. A summary of his smooth cylinder results is shown in Fig. 4.10. In this figure, the lift coefficient (C_L) is plotted against the Reynolds number for constant values of Keulegan-Carpenter number. For Reynolds numbers smaller than 2×10^4, C_L depends primarily on the Keulegan-Carpenter number. In the Reynolds number range from about 2×10^4 to 1×10^5, C_L depends, to varying degrees, on both the Reynolds and Keulegan-Carpenter numbers. Above a Reynolds number of about 1×10^5, the dependence of C_L on Reynolds and Keulegan-Carpenter numbers is quite negligible, but in general, values of C_L drop rapidly with increasing Reynolds

and Keulegan-Carpenter numbers, and levels off to about 0.2 for large values of Reynolds and Keulegan-Carpenter numbers.

Sarpkaya (1976a), in discussing the application of his planar flow results to wavy flow conditions, reported that the lift coefficient may be about 30 percent smaller than that presented in Fig. 4.10 for KC values smaller than about 30, primarily because of the reduced spanwise coherence. However, the differences between the wavy flows and planar oscillatory flows are negligible for larger values of the Keulegan-Carpenter number and lift coefficients presented in Fig. 4.10 may be used to calculate the transverse lift forces.

4.6 Hydroelastic Interaction

Hydroelastic interaction is the phenomenon caused by the relative motion, or vibration, of an immersed structure, and the resulting hydrodynamic force on the structure. Because the vibratory response of the cylinder structure is related to the applied hydrodynamic force, and the hydrodynamic force is in turn influenced by the motion of the structure, both the hydrodynamic force and the structural response are interrelated. The relative motion and vibratory response of the structure also affect the value of the drag coefficient. Flow-induced oscillation has been a subject for numerous research studies. A comprehensive review on this topic was given by Sarpkaya (1979).

In applying the Morison Equation to the in-line vibrations of a cylinder undergoing displacements which are small compared to the diameter of the cylinder, the interaction equations of equilibrium are usually modified to account for the relative motion, (i.e., the water particle velocity (u) and acceleration ($\dot{u}$) minus the structural velocity ($\dot{x}$) and acceleration ($\ddot{x}$) in calculating wave forces, rather than just the velocity and acceleration of the water particles alone). Thus, the Morison Equation may be rewritten in the form below as

$$F = \rho(C_M-1)\ V\ (\dot{u} - \ddot{x}) + \rho V\dot{u} + 1/2\,\rho\, C_D\ A\ |u-\dot{x}|\,(u-\dot{x}) \qquad (4.2)$$

where F is the total force on the member. The first term on the right-hand side is the added mass term associated with the convective acceleration of the relative motion which occurs because of the changing flow around the structure. The second right-hand term is the Froude-Krylov force due to the local acceleration of the unsteady flow. This term is affected only by the relative location of the structure in the wave, which is often considered as unchanged for small structural displacement problems. The third term gives the drag force due to the relative velocity.

In conducting dynamic analysis of the structure, Equation 4.2 can be equated to the equation of motion of the system as:

$$M\ddot{x} + C\dot{x} + Kx = (C_M - 1)\rho V (\dot{u} - \ddot{x}) + \rho V\dot{u} + 1/2\,\rho C_D A|u - \dot{x}|(u - \dot{x}) \tag{4.3}$$

where X is the structural displacement, and M, C and K are the structural mass, damping and stiffness respectively. Equation 4.3 can be rewritten as:

$$[M + \rho(C_M - 1)V]\ddot{x} + C\dot{x} + Kx = \rho(C_M - 1) V\dot{u} + \rho V\dot{u} + 1/2\rho C_D A|u - \dot{x}|(u - \dot{x}) \tag{4.4}$$

The drag force term on the right hand side of Equation 4.4 still relates to the structural response, $\dot{x}$. Since this is a nonlinear term containing the absolute value term $|u-\dot{x}|$, it is difficult to uncouple $\dot{x}$ from u. For rather rigid structures, the structural velocity is much smaller than the water particle velocity, u, and the relative velocity, $(u-\dot{x})$, can be and is replaced by the water particle velocity, u.

A solution based on such a linearization shows, in general, that the dynamic response contains resonances of the cylinder with the inertial and drag components of the fluid force. When the natural frequency of the cylinder approaches the frequency of the oscillatory flow, the cylinder will resonate with the fluid

force, and the response of the structure at resonance is limited only by the damping of the fluid-structure system.

The dynamic behavior of an offshore structure is a complex phenomenon, and may become very significant in deep water conditions when the fundamental periods of the structure become comparable to the design wave periods. This phenomenon tends to produce near resonance structural response conditions leading to larger stresses than would be predicted from a conventional pseudo-static analysis.

Transverse vibrations of structural members have been discussed in Section 4.5. It was shown that they can occur when the vortex shedding frequency is nearly in tune with the natural frequency of the structural member, and can cause dynamic as well as fatigue damage to the structure. The forcing function is not yet accurately known for oscillatory fluid motion, and will have to be determined experimentally. In general, the sharpness of the vibrations depends on the internal damping of the structural system.

Very limited data are available for describing the values of force coefficients for oscillating structural members. Sarpkaya (1977) conducted a study of transverse oscillations of a flexibly-mounted rigid cylinder in harmonid flow. He reported that the ratio of the maximum lift coefficient for the oscillating cylinder to that for the stationary cylinder is about 1.8 for a Reynolds number range of about 6 x 10^4, and a Keulegan-

Carpenter number of about 54. For oscillations of continuous structures, such as space frames, the situation is even more complex due to other factors such as the sheltering effect of the interconnecting members, angle of inclination of the waves and currents, etc. Before more accurate data can be developed, the force coefficients for rigid cylinders are usually used in performing dynamic analysis of offshore structures.

4.7 Effects of Wave-Current Interaction

In offshore structure design, the presence of currents complicates the application of the Morison Equation, whose kinematic terms were originally associated with only that of waves. The conventional method of including the current effects on wave loadings is by superimposing current profile over the wave velocity field generated in the absence of a current. Hogben, et al. (1977) suggested that for a current flowing approximately parallel to the wave direction, the current velocity should be added vectorially to the wave particle velocity both for the definition of Reynolds number, and for use in the Morison Equation. The evaluation and meaning of the Keulegan-Carpenter number when such a current is present is uncertain. Since the Keulegan-Carpenter number is essentially a measure of the relative magnitude of drag to inertia, it is suggested that in most situations, the vectorial sum should be used until more reliable data are available.

The presence of a current seems to influence the drag coefficient and not the inertia coefficient, since the current changes the velocity field and sweeps the vortices away from the structure. It is to be pointed out that recommended drag coefficients inferred from real sea conditions, such as the Wave Force Project I and II experiments, did not consider the separate effect of currents and waves. This is due to the difficulty in obtaining and analyzing wave force and current data together, as well as the lack of an accurate model for describing the wave-current field. A re-analysis of the Wave Force Project II data by Dalrymple (1976) indicated that drag coefficients obtained without considering the presence of a current are too large. The bias introduced by the current can change the C_D values as much as 30 percent, depending on the relative magnitude of the current to the maximum water particle velocity.

A limited amount of research work has been done on the understanding of wave-current interaction phenomenon, and the present state of knowledge on this subject is far from adequate. Longuett-Higgins and Stewart (1961) first reported the change of wave characteristics when a wave encounters a current. If the current is in the direction of the waves, wave amplitude decreases and wave length increases. If the current opposes the waves, then the wave steepens and shortens. In a random wave field, component waves are affected by currents in a similar manner, resulting in the modification of the wave spectrum (Tung

and Huang, 1973). Dalrymple (1974) developed two wave models for the representation of symmetric finite amplitude water waves of arbitrary order propagating on currents with velocity profiles which are describable by one or two straight lines. He compared his results in computing the fluid particle velocity with the conventional method of superimposing the ambient current velocity profile onto the velocity field of a wave in still water. It was noted that the error in superposition is quite small in the deep water range, although the superposition method is known to be theoretically incorrect due to the nonlinear interaction of the current and the wave. Superposition of waves and currents does not account for the change of wave characteristics due to currents.

The effect of currents also affect the breaking limit of waves as reported by Dalrymple and Dean (1975). They showed, by using an iterative procedure which relates a wave propagating on a constant and uniform current to an equivalent wave propagating in still water, that the presence of current tends to increase the limiting wave heights when the current flows in the direction of the waves and to increase the percentage of wave crest above still water. The opposite effect is true for opposing currents.

4.8 Surface Effects

An important problem area for which the Morison Equation is not directly applicable arises in the so-called "splash zone" of offshore structures. In this zone, horizontal bracing members

and vertical members piercing the water surface are subjected to very heavy cyclic buoyancy forces and slamming loads. Under these conditions, the regular wave theories are not adequate to describe the free surface wave kinematics, and the wave loads depart from the drag and inertia concept prescribed by the Morison Equation. In some cases, these free surface effects can cause severe vibrations due to the impulsive nature of the slamming forces, making the structure highly susceptible to fatigue. These problems are of some urgency, but relatively little is known at present.

Some of the most severe wave loads are on horizontal members near the free surface that are repeatedly submerged, and subjected to a form of cyclic buoyancy and slamming in each wave cycle. Several such fatigue-related "splash zone" failures have been reported by Altfield (1975). Recent research studies on this subject have been concentrated on identifying and quantifying the different components of slamming loads and the parameters that determine them.

Wave slamming is the impact load on a surface piercing member during the initial stages of fluid contact which develops as the large particle accelerations give rise to large forces. As the member becomes more fully immersed, forces due to viscous effects become predominant.

Kaplan and Silbert (1976) developed a method for computing the forces acting on a horizontal cylinder from the instant of impact to full immersion. They reported that this force is equal to the sum of the buoyant force and the time-rate of change of momentum. Thus, one has

$$F = \rho g\ A + (m + \rho A)\ \ddot{\eta} + \frac{\partial m}{\partial z} \dot{\eta}^2 \tag{4.7}$$

in which F is the total force on a unit section length of the cylinder member; ρ , the fluid density; g, the gravitational acceleration; A, the immersed area; m, the added mass per unit length; η , the instantaneous height of the wave surface above the mean water level; and z, the instantaneous depth of cylinder immersion. The first and second derivations of η with respect to time are denoted by $\dot{\eta}$ and $\ddot{\eta}$.

Dalton and Nash (1976) conducted slamming experiments with a 0.5 inch diameter cylinder with small amplitude waves generated in a laboratory tank, and tried to correlate the slamming force, F_s, with a slamming coefficient, C_s, as

$$F_s = 1/2\ C_s\ \rho\ Ap\ U^2 \tag{4.8}$$

where A_p is the projected area of the member normal to the plane of wave impact, and U is the resultant fluid velocity during impact. Their data exhibited large scatter, and showed no

particular correlation with either the predictions of the hydrodynamic theory or identifiable wave parameters.

Miller (1977) presented the results of a series of wave-tank experiments which were made to establish the magnitude of the wave force slamming coefficient. He found an average coefficient of 3.6 for those trials in which slamming force was dominant. Faltinsen, et al. (1977) investigated the load acting on rigid horizontal circular cylinders which were forced into motion with constant velocity through an initially calm free surface. They found that the slamming coefficient ranged from 4.1 to 6.4. For flexible horizontal cylinders, they found that the analytically predicted values were always lower than those found experimentally. Experiments in controlled planar oscillary flows were also done by Sarpkaya (1978a). He confirmed that the initial value of the slamming coefficient is essentially equal to its theoretical value of π. He also reported that the force experienced by the cylinder cannot be considered independently of dynamic response of the cylinder. In fact, the slamming coefficient can be amplified to a value as high as 6.3 through the dynamic response of the cylinder.

Kaplan (1979) presented another model which describes both the vertical and horizontal force acting on the horizontal member in the free surface zone. The expression for the vertical force, F_z, (position upward) on the circular section of a member was reported by Kaplan as

$$F_z = \rho g A\eta + (m_3+\rho A)\ddot{\eta} + \frac{\partial m3}{\partial z}\dot{\eta}^2 \qquad (4.9)$$

where m_3 is the vertical added mass of the section as a function of the degree of immersion.

The first terms on the right represents the buoyant force, the second term represents the effect of the spatial gradient in the waves, and the third term represents the results of determining the time rate of change of fluid momentum. This expression was derived on the basis of ideal potential flow which accounts for inertial fluid forces associated with impulsive flow at the free surface. It is also assumed that the cylinder radius is small compared to wave dimension, so that the wave is locally flat and horizontal across the cylindrical section. An expression for the horizontal force, F_y, was also given as

$$F_y = (m_2 + \rho A)\dot{u}_o + \frac{\partial m_2}{\partial z}(\dot{\eta} u_o) \qquad (4.10)$$

where m_2 is the horizontal added mass of the immersed section, u_o and $\dot{u}_o$ are the wave particle velocity and acceleration in the horizontal direction, and $\frac{\partial m_2}{\partial z}\dot{\eta}$ is the rate of change in immersion.

This theoretical model has been calibrated with real sea data obtained from the Ocean Test Structure experiment (Kaplan, 1979). The correlation between theory and experiment for the

vertical impact forces was not adequate. However, Kaplan (1979) supported the findings of previous studies. He showed that a slam coefficient equal to π or approximately 3.2, may be used in design in spite of some of the present problems of full-scale data correlation. Correlation of the horizontal force with the full-scale test data showed better representation of the actual horizontal impact force.

4.9 Structural Members Near the Sea Bottom

The determination of wave forces on submerged horizontal cylinders near the sea bottom is an important subject, as it involves practical design problems such as design of submerged pipelines and ocean outfalls. In spite of various research efforts, the knowledge of wave forces on submerged horizontal cylinders is still incomplete. This difficulty arises from the lack of an accurate description of the fundamental mechanisms for vortex formation about a horizontal cylinder located on, or close to, the bottom in periodic flow.

In computing wave forces on horizontal members near the sea bottom, both the horizontal and vertical force components need to be considered. The horizontal forces can be determined with the usual Morison Equation formulation by considering the drag and inertia force components in the horizontal direction. However, the vertical forces are composed of the drag and inertia components in the vertical direction, plus the additional lift force due to vortex circulation. The vertical drag and lift

forces are usually lumped in one single lift term so that the total vertical force on a sectional length (ℓ) of a horizontal cylindrical member can be formulated as

$$F_T = C_L \rho 1/2 \, D \ell u^2 + C_M' \rho \frac{\pi D^2}{4} \ell \dot{u} \tag{4.11}$$

where C_L = total lift coefficient

C_M' = inertia coefficient in the vertical direction

The force coefficients for horizontal cylinders are similar to those of regular vertical cylinders, except that they are subject to proximity effects when the member is close to the sea bottom.

In deep water conditions, away from the free surface, the fluid orbit path is relatively small compared to the member diameter due to the exponential decay of the particle orbital motion. These conditions have been depicted in Regime V in Fig. 3.3, where the ratios H/D and πD/L are small. At a water depth of 300 ft. under a surface wave height of 30 ft., this regime represents conditions where the ratio of particle motion to member diameter, approximated by H/D, becomes less than about 6.0, or that the member diameter becomes larger than 5 ft. This regime would also apply to smaller structural diameters under smaller waves and deeper water. In this regime, the drag force is not significant. The remaining acceleration and lift forces can be determined analytically by potential flow theory. This

method has been substantiated by experimental works of Nath and Yamamoto (1974), and Yamamoto, Nath and Slotta (1974). Their studies also reported that theoretical horizontal and vertical inertia coefficients are the same, and the lift coefficient and the vertical inertia coefficient depend on the pipe clearance, ϵ, from the sea bottom. It was shown theoretically by Dalton and Helfinstine (1971) that in this regime the lift coefficient approaches negative infinity as the pipe clearance approaches zero, and is equal to 4.49 when the pipe clearance equals to zero. The theory also predicts that the vertical inertia coefficient will become larger when the cylinder is closer to the bottom.

In shallower waters, or when the ratio of particle orbit path to member diameter is large enough for the periodic formulation of vortices, the drag force will become important and the potential flow theory is no longer valid. Grace and Nicinski (1976) performed a field measurement study on wave forces on pipelines near the ocean bottom, and provided some suggestions for selecting design values on wave force coefficients. They reported that the horizontal drag force coefficients are related to the ratio of the orbit particle path to the member diameter, S/D. A plot of their results is shown in Fig. 4.11. The drag coefficient was found to decrease with increasing S/D to an asymptotic value of 0.7. A tentative upper bound curve was

suggested for design to include the effect of various pipe clearances from the sea bottom.

A plot of Grace and Nicinski's results on the inertia coefficient in both the horizontal and vertical direction is shown in Fig. 4.12. The inertia coefficient was found to depend on the ratio of pipe clearance to member diameter, ϵ/D. Grace and Nicinski recommended an inertia coefficient of 4.0 for zero pipe clearance to be used for design. They also suggested obtaining inertia coefficient values from the curve in Fig. 4.12 for other pipe clearances.

The relative particle motion to member diameter ratio S/D also strongly influences the value of the lift coefficient C_L. A plot of Grace and Nicinski's results shown in Fig. 4.13 indicates a general trend for the lift coefficient to drop off with increasing S/D up to a limit, at which point the lift coefficient increases and then again subsides. Grace and Nicinski also suggested using the upper bound C_L values for design. Results presented by Grace and Nicinski (1976) are for horizontal pipelines parallel to the wave fronts. Other effects on force coefficients such as skew angles of wave attack, bottom current-wave interactions and pipe groupings, etc., still require additional study.

5.0 RESEARCH NEEDS

5.1 Overview

This section summarizes, organizes, and discusses those research needs which can result in improvements to the Morison Equation or can result in a new formulation or method of analysis filling the need for the Morison Equation. Section 6 will summarize our evaluation of these research needs, and suggest priorities. Section 7 will summarize our recommendations for pursuing these research needs.

In the 30 years since the introduction of the Morison Equation, there have been significant improvements in our understanding of waves, wave forces, flow of water around structural elements in an ocean environment, performance of offshore structures designed with the Morison Equation as an ingredient, and in our general analytical and design capabilities. As discussed in Section 3.0 of this report, the original Morison Equation has undergone slow and rather non-uniform evolution during this period. In addition, the variables describing the ocean kinematics are presently used in several different manners, depending on the application (e.g., combined wave-current effects; effects caused by inclined members or obliquely incident horizontal members; the use of the total or local derivative, etc). In other applications, additional force

terms (e.g., to account for transverse (lift) forces) are used. Finally, various designers apply different empirical "correction" coefficients to the individual force component terms, as well as to the entire expression in order to incorporate their experience with structures designed for similar environmental and strength requirements.

The overall effect of the Morison Equation evolution has been the development of a patchwork of only partially standardized design procedures.

With this background of significant improvements, pragmatic evolution, and with the increasing needs to improve our general capabilities to accurately describe or characterize wave forces, additional research is needed and warranted.

We have organized the research and development effort we perceive to be needed into four general areas (also shown schematically in Fig. 5.1):

1. Updating of the Navy's design guideline for determining wave forces on structures.
2. Improvements and extensions to the Morison Equation.
3. Improved descriptions of the sea state and the associated water column kinematics.
4. Basic research on fluid-structure interaction dynamics.

The specific research needs within each of these four general areas will be discussed in detail in the following sections.

5.2 Updating of the Navy's Design Guideline for Wave Forces on Structures

The present NCEL wave force design guideline (NAVFAC DM-26, 1968) is developed directly from the original Morison Equation. A substantial difference exists between this NCEL design procedure versus the design procedures which are currently in use in the offshore hydrocarbon industry. Section 3.0 of this report has outlined many of these differences, and in that section, it was indicated that no truly standard design procedure exists.

The fact that the wave force design procedures used by the modern hydrocarbon industry depart substantially from the older standards used by NCEL indicates a need for NCEL to support a development effort which will synthesize and incorporate the most valuable elements of the wave force design procedure used in industry today.

This first and major need of the NCEL research and development program is basically a development effort. That is, the information presently available and disseminated among commercial users can be assembled and translated into an updated guideline for designing Naval offshore structures. In accomplishing this effort, it will be necessary to keep in mind the Navy's own special need. For example, the functional purpose of many Naval offshore structures is quite different from most of the commercial offshore structures. Commercial offshore structures are often designed with a large margin of safety

factor because of the substantial investment, expensive equipment, and personnel on these structures. Many Naval structures are simple ones which are unmanned, and are used to support relatively inexpensive electronics equipment. Thus, the design guideline developed for the Navy should be specially written to limit the potential for expensive overdesign.

5.3 Research Needs for Improving and Extending the Morison Equation

As discussed in Sections 3 and 4 of this report, the Morison Equation was originally formulated for a much simplified and idealized set of conditions. However, the equation has also been extended to other conditions of various complexities with varying degrees of success. Research efforts are needed for achieving improvements and more reliable extended usage of the equation. A primary research objective would be, based on our current improved understanding of the general wave force problem, to properly analyze, summarize and incorporate the background of analytical, laboratory experimental, and field data gathering efforts of the past 30 years into an extended Morison Equation, which can be termed as a Unified Wave Force Formulation. The Unified Wave Force Formulation may be regarded as an orderly and systematic design procedure which would allow the designer to fully recognize and reliably characterize the complex wave force components necessary for a successful design of Naval offshore structures.

In development of such a Unified Wave Force Formulation, designers need to be able to reliably describe the wave forces on structural elements and assemblages of structural elements in complex sea-structure interaction environments. The designer also needs to be able to reliably characterize the applications of wave force computations under different design frameworks, based on the temporal, spectral and probabilistic philosophies of analysis. The general effort can be organized into six research tasks as shown schematically in Fig. 5.2:

<u>Task 1</u>

The first task concerns a better characterization of complex conditions associated with single structural elements. This includes a list of complications such as vortex-induced lift forces; near-surface wave slamming effects; near-surface cyclic buoyancy forces; inclined member effects; member surface roughness effects; vibrating and compliant structure motions; noncircular cylindrical sections; and breaking-wave-induced forces, that are outside the original scope of the Morison Equation.

Improvements in the above areas can be achieved by adopting one or a combination of the following approaches:

1. A better quantification of force coefficients, such as for conditions complicated by roughened members and noncircular cylindrical members.

2. A better description of the complex conditions by introducing additional force terms or separate formulations, such as for vortex-induced lift forces, near-surface wave slamming forces, and cyclic buoyancy forces. This would require the addition of more terms to the original Morison Equation.
3. A better characterization of the fluid-structure kinematic conditions that are complicated by influences such as inclined members, vibrating and compliant structure motions, and breaking wave conditions. This effort is likely to result in better ways of characterizing the wave orbital velocities and accelerations for use in the Morison Equation.

As discussed in Section 4, due to numerous wave force studies worldwide, some progress has been made toward a better understanding of the above complex wave-loading conditions. However, much research effort is still needed in terms of both theoretical and experimental endeavors, until a more reliable characterization of these conditions can be achieved.

Task 2

The second task deals with the complex conditions that are associated with assemblages of structural elements. This task includes the same list of complications that are associated with Task 1, but represents an extra level of complexity, as we are

now concerned with the additional influence of multiple members of a structure, including wave forces on structures with widely separated elements, and on structures with closely spaced elements.

Complex structures, such as template-type platforms, consist of a conglomeration of multiple vertical, horizontal and inclined members and are, at any given instant, subject to widely differing force inputs, with some in line with the principal wave direction, and some transverse to it; some at the wave frequency, and some not. The picture is further complicated by the mutual interferences of neighboring members and the time-wise and spatial random variation of the sea itself.

This task is primarily concerned with global force computations on the entire global structure such that research results obtained from Task 1 that are associated with single structural elements may not be directly applicable to this case. Separate or parallel research efforts, such as those in Task 1, are needed until the separate influences of different complex conditions can be fully quantified.

Task 3

The third task concerns research needs to obtain better characterization of the time domain analysis method of computing wave forces on complex structures. This task is particularly concerned with the temporal characterization of wave forces including unsteady flows, and deterministic and nondeterministic

descriptions of wave forces on structures in time-space, force dimensions. Part of the problem that needs attention is similar to that discussed in Task 2, in that, due to time-wise and spatial variation throughout the entire global structure, the fluid flow condition is quite unsteady and complicated. The complications are a result of a mixture of multiple influences of inline and transverse forces; different force inputs from wave components with different wave directions and frequencies; the nonlinear variation of forces due to nonperiodic waves and other random variations of the sea surface; and the variation of force coefficients throughout wave cycles. It is likely that the complexity of the situation can reduce the total predicted loads on the entire structure considerably from the levels that would exist if all members behaved uniformly at a single instant, such as assumed in the conventional pseudo-static design wave method. Research efforts are needed to develop better descriptions of this temporal characterization problem.

The other part of the problem in this task deals with deep water or compliant structures, where the time-dependent properties of wave forces coupled with the dynamic response characteristics of the structure becomes important. Some of this class of structures are designed to respond compliantly to the motion of sea waves, such as tethered floating platforms and deep water guyed towers. For all these cases, the relative velocities between symmetrical elements and fluid particle motions are

affected by the dynamic response to a certain degree. The response will then, in turn, influence the flows and wave forces in various interactive ways. It has been discussed in the previous section on hydroelastic interaction that the conventional way of handling such a condition is by adopting the linear relative velocity hypothesis. This hypothesis has a major influence on the calculation of structural resonse if the structure responds dynamically to the fluid excitation. Research to clarify this aspect of fluid-structure interaction is of great importance.

Task 4

The fourth task of research efforts for improving the Morison Equation deals with its applications to compute wave forces in the frequency domain. This task particularly concerns the spectral characterization of wave forces including descriptions of wave forces on structures necessary for long-term fatigue and dynamic response studies. In a spectral wave force analysis, structure responses are computed from a sea surface frequency spectrum by way of a force transfer function, utilizing a wave force theory such as the Morison Equation (Pierson and Holmes, 1965; Borgman, 1967). This spectral method automatically provides a full statistical description of loads and responses. The method can also be expanded to include directional spreading information by adopting the directional spectra concept.

In general, the linear random wave theory based on a spectrum of surface elevation and a multi-variate Gaussian process for particle kinematics provides a good first order model for specifying the wave field incident on an offshore structure. However, extensions of the model are probably required if the flow within the free surface is to be properly represented for steep waves (Holmes and Tickell, 1979). There is also a need to extend the Morison Equation to deal with the combined action of forces components in-line and transverse to the instantaneous flow direction.

Research is also needed toward a generalization of the theoretical framework underlying spectral analysis by including the possibility of handling nonlinear wave and force effects.

Task 5

This task involves items leading to improvements of the probabilistic wave force computation method which recognizes the random environment of a natural sea, and treats wave forces as statistical rather than deterministic quantities. The Morison Equation is recast in the form of a relationship which relates the stochastic wave kinematics to the resulting, statistically distributed forces on structural elements. The force coefficients are also treated as statistical parameters. It appears feasible to include the directional spreading of the real sea as well, and even to extend it beyond the computation of wave forces alone by including dynamic structural response. However,

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ASSESSMENT OF THE MORISON EQUATION.(U)

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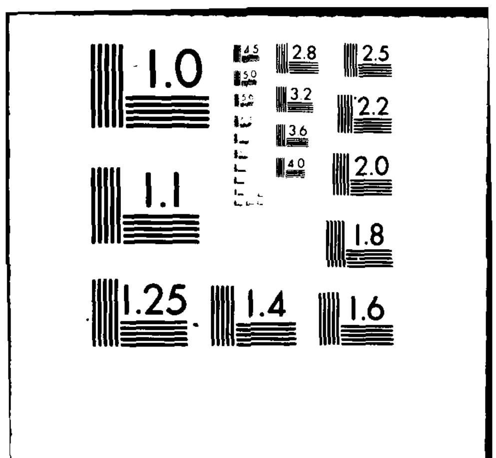

MICROCOPY RESOLUTION TEST CHART

much research effort is needed to overcome difficulties in attempting to determine the joint probability distribution of forces acting simultaneously at multiple members of a complex structure.

The form of probabilistic wave force determinations which show great promise is the conditional similitude of random waves. In these analyses, the first problem is to determine a wave spectrum that characterizes a particular problem. Research is presently under way to determine the most probable extreme time series which might occur within the constraints of this design wave spectrum (Borgman, 1980). The specific time series with high probabilities of occurrences can then be used with a Morison Equation-type analysis to determine extreme wave forces associated with the design storm. This work is relatively new, and shows great promise for advancing the use of the Morison Equation in both extreme and normal design conditions.

In addition to the relatively new area of conditional similitude for random waves, work is under way to develop a nonlinear directional transfer function between wave kinematics and the resulting forces on the structures. This transfer function is based on a form of the Morison Equation. The major emphasis of the research is put upon the development of spectral techniques which permit the simultaneous utilization of both nonlinear wave characteristics (which are nondispersive), and the realistic directional propagation and interference of these

nonlinear waves. Research in this area has the potential opportunity of providing the designer with a method for applying the Morison Equation to a real characterization of ocean kinematics. The results of this work are likely to have substantial impact in improving the quality of the design of future offshore structures.

Task 6

Upon successful characterizations of complex wave-structure conditions, and different design frameworks in the temporal, spectral and probabilistic domains, improvements and extensions of the Morison Equation and the development of the Unified Wave Force Theory cannot be completed without a better quantification of the empirical force coefficients, consistent with the results of the five previously cited tasks.

As discussed in the previous section on force coefficients, considerable uncertainty still exists in the selection of the appropriate force coefficients for design. The main difficulties of this task include the inherent complexity of the loading mechanisms; the scaling barrier that exists between the low Reynolds number conditions normally attainable in the laboratory and the turbulence of full-scale conditions; and the variability and randomness of the particle kinematics in the real seas for which force determinations are required.

Due to the apparent scaling barrier problem of most laboratory facilities, wave force data are deficient in the supercritical and postcritical Reynolds number range, where most of the full-scale wave structure conditions exist. Full-scale measurements at sea are clearly needed, for they avoid the problem of extrapolating from smaller scale test data. Such experiments will also automatically include the influences of all the elements of real seas that one cannot simulate fully in laboratories. An important drawback of prototype scale measurements is that the inherent inter-relations of different physical elements and phenomena have to be unravelled before the nondimensional force coefficients can be determined. An example is the importance of simultaneous measurements of wave force data and the local particle kinematics, so that the complexity of the force data would not be complicated by the added uncertainty of having to derive particle kinematics from wave theories of unknown accuracy.

Laboratory measurements are also important in that they can provide insight into the separate influences of all the relevant complications of wave force loading by way of idealized models under controlled conditions.

In Section 3 of this report, the problem of determining the appropriate values of the drag, virtual mass, and transverse (lift) coefficient values for varying design conditions was described in detail. It was pointed out that recent attempts to

identify the parameters which govern these coefficients have shown better promise. In limited ranges of the Reynolds and Keulegan-Carpenter numbers, this parameterization has been rather successful. However, much more work is necessary to develop a complete description of the variation of the force coefficients in conditions which presently defy appropriate parameterization. This work needs to be directed at extending the list of dimensionless parameters which control the behavior of the force coefficients, as well as determining the relationship between governing parameters and coefficient values. Most of the research will be based upon extended laboratory work

Areas that are particularly in need of more data are those that are affected by: surface roughness, interference from neighboring members, inclined members, vibrating or compliant members, and irregular member geometries and shapes. Descriptions of the cause of the complications for these conditions have been discussed in the previous section on the extension of the Morison Equation. With the achievement of better characterizations of the above complicated conditions, this knowledge should be used fully as a guidance toward better planning of future wave force experiments, both in laboratories and at sea, and in interpreting the test results in determining their reliability and applicability.

Upon the availability of data from more major wave force measurement programs (such as the Ocean Test Structure Experiment, the Conoco Test Structure Experiment, the Christchurch Bay Tower Experiment, etc.) which have extended the measurements to more complex conditions at sea, and the abundance of laboratory wave force experiments in controlled conditions, it seems that a timely effort would be to seek a collaborative and systematic effort to distill all the data in order to produce more appropriate and reliable force coefficients consistent with updated force formulations such as the Unified Wave Force Theory.

5.4 Research Needs to Improve the Description of Wave and Current Kinematics

This report is devoted to examining the Morison Equation. Strictly speaking, the subject of wave and current kinematics is beyond the scope of this project. If our understanding of these kinematics was complete, then the present version of the Morison Equation would produce much more reliable results than is presently possible. However, our ability to provide appropriate values of wave and current kinematics is presently so limited as to cause this to be a major source of error in all design and research applications of the Morison Equation.

It appears likely that future commercial and Naval fixed ocean structures will be located in increasingly deeper waters. This will cause our lack of understanding of wave and current

kinematics to be even more significant in limiting our ability to determine the forces on these structures through the use of the Morison Equation or its successor. Furthermore, many of the deep ocean structures are to be compliant, and will require good description of the relative motions of the fluid and structure as well. For these reasons, it is significant to briefly mention the major areas of wave, current and structure kinematics which can be improved by future research.

Figure 5.3 shows the general categories and individual subjects which represent important research needs to improve the description of wave and current kinematics. There are three general categories:

1. Better characterization of the wave field;
2. Better characterization of nonwave water column motions; and
3. Interactions (including characterization of the motions of the structure)

The individual topics organized within these three categories are discussed below.

5.4.1 Better Characterization of the Wave Field

Although much work has been done in studying ocean waves, this area is so important and complex as to require much more research. Many aspects of ocean waves remain poorly studied and deserve future work. The aspects of ocean wave research which are likely to have most impact on developing more reliable

application of the Morison Equation are discussed in the following sections.

● Velocities and Accelerations

In Section 3.5 of this report, the subject of wave kinematics was treated. It was pointed out that a normal procedure for estimating wave velocities and accelerations is to select an appropriate wave theory to compute the orbital motions from a design wave height or from data on the sea surface elevation history. Figure 3.8 shows one mapping of appropriate wave theories using the parameters H/T^2 and h/T^2. It represents one of many wave theory application maps which have been developed. The different application maps result primarily from differences in the criteria used to judge the performance of the various wave theories. Laitone (1962) used a comparison based on wave celerities. Taylor (1955) used agreement of the wave surface profiles with qualitative observed data as his criteria. Komar (1976) used as his criteria the desire to assign the widest possible regions to the simplest wave theories, as well as failure criteria based primarily on the free surface kinematic boundary condition. Dean (1970) used the relative error in the kinematic and dynamic free surface boundary conditions to index the validity of the wave theories tested. He also points out that good agreement of two theories in one parameter does not assure agreement of other parameters. Dean illustrates this by demonstrating that over an appropriate range of wave conditions,

solitary wave theory and stream function wave theory satisfy the kinematic free surface boundary condition exactly. Furthermore, for an important range of wave conditions, Fifth Order Stream Function Theory and Stokes Fifth Order Wave Theory provide good fits for the dynamic free surface boundary condition. However, when very high (tenth) order Stream Function Theory is used as an arbitrary criteria to which the other theories are compared, all theories show wide departures in several parameters. Furthermore, when this same approach is used in estimating total drag forces, he shows departures of approximately 1 percent for solitary, Fifth Order Stokes and Fifth Order Stream Function theories in intermediate water depths, and 5 to 30 percent in shallow water conditions. When the higher order stream function theory is compared to Airy Wave Theory and Cnoidal Wave Theory, differences as high as 105 percent in the prediction of total drag forces result. Although the calculated wave forces are not meant to judge the validity of the theories, these results illustrate the difficulty faced by a designer in selecting an appropriate wave theory. All this serves to illustrate the great uncertainty that presently exists concerning the appropriate selection of a wave theory to apply in calculating wave orbital kinematics.

There is a dearth of oceanographic data which can be used to appropriately evaluate the various wave theories. One paper, by Thornton and Krapohl (1974) reports on an experiment conducted

aboard the Naval Undersea Center oceanographic research tower at San Diego, California in a water depth of 19 meters. Current meters were located at different depths beneath a wave staff so that simultaneous measurements of the sea surface and wave kinematics were accomplished. The experiment showed that wave-induced velocities were 2 to 4 percent greater than those calculated by Linear Wave Theory. This one experiment illustrates the validity of Airy Wave Theory under low wave conditions, and also illustrates a class of field experiments that are necessary to fully define the range of applicability for the various wave theories under real ocean conditions.

Another study by Forristall, et al. (1978) compared measured storm wave kinematics with results of wave theories. Although significant over-prediction of orbital velocities was noted for both regular and irregular wave theories tested, they note that composite linear wave theory can be brought within ten percent agreement with direction spectral descriptions of the storm conditions.

These two studies indicate how little is known about the validity of wave theories in predicting in-ocean wave kinematics. Much more field experimental work is needed before the range of applicability of existing wave theories can be fully specified.

● Kinematics of Breaking Waves

The above discussed difficulties in understanding the relationship between actual wave kinematics and the various wave theories which might be used to predict them, is related to an even more intense problem. This problem lies in describing the kinematics of breaking waves. All wave theories previously discussed in this report are developed from assumptions of symmetric wave shapes and nonbreaking conditions. However, as a major use of the Morison Equation is determining the maximum wave forces likely to be applied to an ocean structure, our lack of understanding of the kinematics of breaking waves severely limits the validity of these estimates.

Recent analytic work by Longuet-Higgins (1976), Longuet-Higgins and Cokelet (1976), and Cokelet (1979) have produced a series of numeric expressions for asymmetric steep surface waves and breaking waves. They have shown that unlike low and moderate amplitude conditions, where the orbital velocities are a small fraction of the phase speed, the orbital velocities in breaking waves can exceed the phase speed of the wave. Furthermore, in breaking waves, accelerations approaching 1 g are predicted. In addition, a significant difference in the phase of maximum velocity and maximum acceleration has been demonstrated by the previously cited authors as well as Thornton et al. (1976) and Kjeldsen and Mirhaug (1979).

The applications of experimental or theoretical descriptions of breaking waves in developing estimates of forces on ocean structures is briefly treated by Watanabe and Horikawa (1974) and Peregrine (1979). The latter author points out that the theoretical study of breaking waves is in its infancy. Although the analytic work cited above is showing promise, the application of this analytic work to design algorithms for ocean structures has not significantly developed. Therefore, we can conclude that additional research in the area of analytic, laboratory, and field studies to describe the actual kinematics of breaking waves in deep water is an important area of future research. Furthermore, the application of these studies to determinations of forces on ocean structures is also a vital area for future research. This problem will be complicated by the need to include impact forces on structural members that are only partially submerged. This may involve extending or rewriting the basic Morison Equation.

- Nonlinear Wave Current Interactions

In addition to the previously discussed areas for research to better understand wave mechanics, it is important to point out that normal design procedure utilizing the Morison Equation for conditions where ocean structures are affected by the combined action of waves and currents is to linearly superimpose the two flow fields. However, this is known to create errors as a result of ignoring the nonlinear interactions between currents and

waves. For simple monochromatic waves propagating parallel to a steady uniform current with zero velocity gradient, the relationship between changes in the wave length and celerity with current speeds are linear and easily demonstrated. However, as pointed out by Thomas (1979), the effect of this uniform current on the wave amplitude is not readily predicted as the amplitude is an independent parameter. The situation becomes much more complex, and much more poorly understood, when the realistic condition of random waves propagating on turbulent currents which are nonuniform and unsteady. Although aspects of this problem have been studied by Longuet-Higgins and Stewart (1961), Whitham (1974), Perigine (1976, 1979), Lighthill (1967), Longuet-Higgins (1975), Dalrymple (1973), Sarpkaya (1955, 1957), and others, progress has been limited. At present, analytic results are only available for laminar conditions with zero or one-dimensional linear velocity gradients to the slowly varying currents.

As the nonlinear interactions between real ocean current and wave fields cause significant changes in the wave characteristics as well as the kinematics which produce forces on ocean structures, this subject is identified as an area very much in need of further research.

- <u>Short-Crested and Directional Waves</u>

Design waves are generally treated as two-dimensional long-crested waves propagating without change in shape. The real sea is known to be characterized by a complex pattern of intersecting

wave trains producing an unsteady interference pattern in time and space. Directional wave spectral techniques permit a statistical description of the surface wave field and of the wave kinematics which can be applied to ocean structures via a modified Morison Equation, used as a transfer function. However, the actual use of directional spectra depends upon adequate measurement and prediction of the wave fields. In conducting these measurements, the effect of the response function of the transducer array must be considered. In all cases, a large number of transducers are required to accomplish a relatively low level of resolution for the directional distribution of wave spectral components. This has very much limited the use of directional spectra use in design work. A newer technique developed from the maximum likelihood method (Okley and Lozow, 1977) promises to produce better results in relating field measurements of sea conditions to forces generated on structures. However, this technique is relatively new and will require much additional work before it can be routinely used in design analysis.

The problem of fully describing short-crested and directional waves is vital to real development of procedures for predicting wave forces on ocean structures. Common usage today frequently ignores this problem. However, there is an increasing base of unofficial data which suggests that the neglecting of the directional aspect of wave forces is a primary source of the

overconservatism in offshore structural design. A promising area for work to help alleviate these problems lies in developing techniques that combine both the nonlinear behavior of ocean waves with a recognition of their directional behavior. Such work permits much more accurate estimates of wave kinematics to be used in calculating wave forces.

5.3.2 Better Characterization of Nonwave Water Column Motions

The effects of currents on ocean structures are often treated in very generalized manners by platform designers. However, as platforms and structures become more complex, and as they are designed for deeper water, the need to accurately treat the forces developed by currents becomes more important.

In a previous section of this report, a brief description was given of a problem created by nonlinear interaction of the wave field with unsteady nonuniform currents. At present our understanding of the spatial and temporal distribution of currents in the Continental Shelf and deeper regions of the ocean is very limited. This is particularly true for extreme events (storms) where currents can become significant contributors to the overall forces acting on a platform as well as having significant nonlinear effects on the wave field. Basic field studies and analytic studies are needed to produce a better understanding of the currents and current profiles characteristic

of various ocean zones before this information can be applied to the design of ocean structures.

In addition to the problems in understanding the general distribution of currents in Continental Shelf and deep ocean areas, there is a great paucity of information on the turbulence characteristics of various oceanic flows. It appears likely that the future development of commercial fixed platforms, as well as the possible development of Naval fixed platforms, will require designs for great water depths. Under these conditions, the oscillatory flows caused by wave orbital motions will be supplemented by oscillatory flows acting over the deep portions of the structures as a result of turbulence. Therefore, analytic and field studies on the mechanism of oceanic turbulence generation, its relationship to various current profiles, and its effects in generating forces on structures is clearly needed.

Distribution of ocean currents and their related turbulence characteristics are also strongly affected by density stratifications within the ocean. In earlier times when fixed structures in the ocean were located in relatively shallow water, the effect of this density stratification could generally be neglected. However, as ocean structures invade into deeper regions, it becomes important to understand the spatial and temporal distributions of water mass stratifications so that the relationship between the vertical distribution of water masses and the vertical distributions of currents can be predicted.

Normal engineering design practice ignores the possibility for opposed current flows at different depths. These opposed currents can, in some cases, have complicated effects on the wave field and wave kinematics. In other cases, they can result in a significant difference in force concentrations on a deep water structure.

In addition, the relationship between ocean density gradients and internal waves has been well studied. However, very little is known about the relationship between internal waves and forces on ocean structures. These subjects are possible areas for future research.

5.4.3 Interactions

In the preceding two sub-sections of this report, the interactions of various wave components with each other and with various current components have been discussed. However, it is important to point out that structure designers must also consider the area of relative motions. This third area involves the actual motion of the structure under wave forces. Little consideration was given to this problem in the early days of ocean platform design, as the structures were relatively rigid and in shallow water. However, with the design of deepwater platforms and guyed structures (e.g., guyed tower and tension leg structures), the relative motion of the platform becomes significant. Thus, the nonlinear combination of wave kinematics, current kinematics, and platform kinematics needs to be

adequately defined. Perhaps the most important area of these interactions lies in understanding the effect of combined boundary layers in producing drag forces about structural members. The presence of a thin wave-orbital boundary layer is known to affect the boundary layer related to the slowly varying current. This effect is nonlinear and poorly understood. Hence, it is recommended that research be designed to undertake the study of nonlinear interactions between wave, current, and structural motions resulting in better understanding of boundary layer behavior in the generation of forces on structural members.

5.5 Basic Fluid Dynamic Research Needs

Currently, the basis for all design algorithms in engineering practices lie in those studies which develop rigorous physical explanation for natural phenomena. As the intention of this report is to guide the Navy's effort in developing research to expand our capabilities in analyzing wave forces on structures, it is important to briefly include some statements concerning basic research needs. However, these basic research needs are considered to be somewhat remotely related to direct applications to the Morison Equation itself. Results produced in these research areas may take many years to acquire, and additional time will be needed to enter them into design level algorithms. As a result, an exploratory treatment is given to these subjects below.

In general, we can identify two major areas of basic research needs. One area consists of fundamental studies into subjects which will increase our understanding of how various fluid flow phenomena affect the generation of forces on ocean structures. These understandings can then be used to better determine significant modifications to the Morison Equation or in obtaining a better picture of the parameters which control the coefficients used in the Morison Equation. The second area of basic research involves work leading to developing a more comprehensive approach to the subject of forces on ocean structures. It is well accepted, and has been documented in this report, that the Morison Equation represents a primitive expression for the total forces acting on ocean structures. One of its original intents was to stimulate more comprehensive work. It is very clear that this primitive relationship must eventually be replaced by a more comprehensive design tool. These areas of basic research effort are discussed in the following section.

5.5.1 Fundamental Phenomena of Wave Forces Acting on a Cylinder in Periodic Flow

A major source of the uncertainties in applying the present Morison Equation, as well as in developing an understanding for the sometimes erratic behavior of the force coefficients, results from the fact that very little analytic work has been devoted to rigorously describing the natures of oscillating flows around cylinders. Beyond some initial solutions to a few ideal cases,

there is a void with respect to appropriate analytic expressions to fully describe the progressive development of the boundary layer structure, wake structure, and overall flow disturbance resulting from time-dependent flows around cylinders. Work in this area will be painstaking, and progress can be expected to be slow. It is hoped that analytic solutions developed as a result of this basic research effort will permit us to gain insight into describing the "fluid memory" of oscillatory flows. In brief, "fluid memory" is the change in fluid turbulence structure caused by the boundary layer and wake structure flowing past a cylindrical structural member. As the flow reverses, these patterned and unpatterned elements of the turbulence can be advected back past the structural member. Under these conditions, the fluid behavior, which developed during the preceding cycle, strongly influences the development of the boundary layer, vortices, and wake during the next wave cycle.

It is unlikely that a complete description of this phenomenon can result from field or laboratory work. Certainly, some specially designed experimental work can provide insights to the theoreticians studying this problem. However, the actual development of quantitative expressions to describe the behavior, kinematics, and dynamics of oscillating flow about structural members will depend on advancements in mathematical fluid dynamics.

5.5.2 More Basic Analysis of Wave Forces on Ocean Structures

Finally, we must point out that although the Morison Equation has functioned as a very effective design tool, work should proceed on more fundamental analyses of the generation of forces on ocean structures so as to produce a more refined method. As pointed out by Lighthill (1979), the Morison Equation fundamentally forces all users to consider that all forces associated with the irrotational part of the flow to be summarized by the inertia coefficient (C_M) and all forces associated with the rotational portion of the flow to be summarized in the drag coefficient (C_D). In the first approximation, these coefficients produce unifying results. However, there are nonlinear components of the force associated with the irrotational flow and vice versa. It appears that a more refined design algorithm can result from a more complete and perceptive analysis of the fundamental momentum equations of motion resulting in a more exhaustive list of force terms and coefficients which might be empirically evaluated. Such a reformulation has the potential of producing coefficients which can be better related to fundamental parameters.

A further extension of basic research could involve the development of numerical solutions of the momentum equations of motion for fluid flows on ocean structures. Although such a technique is liable to be exhaustive in its development and the results may require extensive numerical programming for each

differing application, it has the potential of producing more reliable results and more fundamental insights than the Morison Equation Method. Such a numerical solution may be of high value for very specialized structures in complex ocean environments.

6.0 EVALUATION OF RESEARCH NEEDS

In the previous section, we have examined a list of potential research subjects. All of these research areas are capable of providing substantial contributions to the design practices in computing wave forces on offshore structures. This section of the report will offer an evaluation of these potential research topics in light of the specific needs of the Navy Civil Engineering Laboratory. Before this evaluation is discussed, it is well to define the major needs and aims of NCEL with respect to its present and future role in the design of Naval offshore structures. At the most general level, two tasks should be considered by NCEL:

1. Updating of the Navy's offshore structure wave force design algorithms to bring its standards in line with current commercial ocean engineering practice;
2. Provide encouragement, organization, and funding of research designed to improve the present methods of computing wave forces on structures via one or more of the existing forms of the Morison Equation, as well as supporting basic research aimed at studying the fundamental principles upon which a more complete wave force design algorithm can be based in the future.

These two general tasks or missions can be characterized as two different forms of activities. These activities are illustrated in Fig. 6.1. The

compilation and conversion of existing design information and data from the research literature to design guidelines code suited to the specific needs of the Navy represents a development effort. The encouragement, organization, and funding of new research to improve the existing state of the Morison Equation or its eventual replacement, is shown on this figure as a research effort.

Task 1

Sections 3 and 4 of this report have demonstrated how the original Morison Equation has been modified in order to both increase the validity of its results, as well as to apply it to a wider range of circumstances beyond which it was originally intended for use. The result is that there is really no standard form of the Morison Equation which is used in all design applications in today's practice. Not only has the original form of the equation undergone numerous modifications, but a substantial body of knowledge has developed concerning the appropriate selection of force coefficients for use in specific problems. Some of these modifications and procedures for selecting the force coefficients have been published. However, much of the other data used in specific design problems is held as proprietary information by commercial design firms and the petroleum industry. Our discussions with personnel from NCEL indicates that the Navy is concerned about their design

procedures lagging behind those of industry (Ward, 1980). Therefore, it appears that the most immediate need facing NCEL is to develop an up-to-date design procedure for computing wave forces on ocean structures. Such a development effort should stress the Navy's special needs to produce structures which are more perceptively and efficiently designed than those which characterize the offshore petroleum industry.

Task 2

Beyond the immediate need for the above-described development effort, there are several important research efforts which should be considered by the Navy. These research efforts are not considered to be able to produce an immediate return to the Navy. However, NCEL should play a key role in directing those areas of research which best advance the Navy's specific needs.

There are several specific areas of research which deserve high priority for encouragement and support. In general, these can be divided into relatively short-term efforts and relatively long-term efforts. The major output from the relatively short-term efforts is directed toward improving the present body of knowledge used with the Morison Equation. The major output of the relatively long-term efforts is directed at developing more fundamental knowledge concerning the fluid dynamics of ocean/structure interactions. This research is likely to result in a different and more comprehensive algorithm for computing wave forces on ocean structures.

• Short-Term Research

The relatively short-term efforts have been described in the first two portions of Section 5 of this report. The highest priority goes to research aimed at improving the state of knowledge about ocean wave kinematics.

1. Wave Kinematics

The subject of ocean wave kinematics remains the most important area where research advances will contribute most profitably to the present utilization of the Morison Equation. Research is needed to answer the question of how to include both the nonlinear and directional behavior of real waves in an analytical or statistical description of ocean waves and wave kinematics. Research in this area will lead to better methods for characterizing real-wave kinematics, which then can be input to the force predicting equations. The results are likely to permit significant refinements to be made in design procedures.

Research has been discussed in Section 5 concerning the use of the Morison Equation as a spectral transfer function between waves and forces on ocean structures. However, much more work is needed before reliable nonlinear directional transfer functions between wave kinematics and the resulting forces can be developed. Such work would probably have i's greatest impact on fatigue studies, but might also be linked with results from studies on conditional similitude of random directional seas for use in extreme wave force predictions.

Research concerning breaking, irregular and asymmetric wave kinematics has been briefly discussed in Section 5 of this report. Recent advances in these areas show that appropriate representations of these real-wave conditions result in descriptions of the resulting kinematics which depart markedly from the results of earlier wave theory. As these forms of waves are often associated with extreme storm events, it is obvious that developing better descriptions of their kinematics will produce more reliable estimates of design wave forces.

2. Parameterization of Force Coefficients

The second major area of relatively short-term research is directed at further work on the parameterization of the force coefficients used with the various forms of the Morison Equation. Section 3 of this report has discussed recent contributions in this area which have proved valuable to designers by providing a quantitative method of estimating the values of the force coefficients in various ranges of the Reynolds and Keulegan-Carpenter numbers. However, there are certain Keulegan-Carpenter and Reynolds number regimes where work to date has failed to produce satisfactory predicting relationships. In particular is the Keulegan-Carpenter number range from about 10 to 20 which has been discovered to produce ambiguous results because of complex vortex action, and the high Reynolds number range ($Re > 10^6$) where data is very much lacking. Therefore, further work in this

area is recommended by conducting more wave force experiments in the field as well as in the laboratory.

- <u>Long-Term Research</u>

The relatively long-term research priorities are more difficult to establish. Significant basic research is generally a highly creative area which is often developed spontaneously as a result of work in allied areas. Work needed to extend or develop an alternative to the present level of Morison-type expressions is generally centered in the area of basic fluid dynamics. The highest priority goes to both experimental and analytic work directed toward producing comprehensive analytic and/or statistical representations of oscillating or wave flow past cylindrical obstructions. Surprisingly little work is available on this subject in the present research literature. The effects of boundary layer-wake interactions need to be more thoroughly researched. A description is badly needed of the memory effects which result when the boundary layer-wake structure of one half of a wave cycle is washed back over the cylindrical structure in the other half cycle.

7.0 RECOMMENDED RESEARCH

7.1 Perspective

The areas of research needs that are discussed and evaluated in the previous sections are all important efforts directed toward the general goal of improving our knowledge of wave forces, and toward the specific goal of improving the design process for Naval offshore structures.

In developing the following recommended research, our focus has been on the specific goal of improving the wave force design process through improvements to the Morison Equation. These recommendations are based on our understanding of the Navy's objectives and resources pertaining to the design of offshore structures.

7.2 Recommendation #1

Our first recommendation is for NCEL to engage in a development, rather than research, effort. The Navy should undertake revision and updating of its design guidelines and practices for determining wave forces on offshore structures in light of the present industrial standards. This undertaking will be non-trivial, because much of the state of practice information is maintained in a proprietary mode by design and petroleum firms. Furthermore, much of this information, data, and methods are unique to individual companies, and no universally accepted method is available. Therefore, it would be the task of this development effort to obtain as much information as possible

concerning the practices and methods used by representative industrial firms, and to synthesize this information into a design guideline best fits the Navy's specific needs while reflecting the most up-to-date approaches.

As the above development effort is to be pointed at the Navy's specific needs, it appears warranted to support an effort to develop a Unified Wave Force Formulation. Such a formulation would be more comprehensive than the basic updating of the Navy's wave force design guidelines in that it would include general methods and practices applicable to many types of fixed offshore structures. Such a formulatin would require a comprehensive integration of both research and design level information. It would be of great use to the public as a whole in that it could be made available to a variety of different-size firms working in various areas related to the production of offshore structures. Furthermore, such a formulation would provide a unified basis for the verification and regulatory activities of other federal agencies concerned with the construction, installation, and operation of offshore platforms, both public and private.

7.3 Recommendation #2

The second area of research recommended for consideration by the Navy is that associated with improved descriptions of design sea states and the associated water column kinematics. While beyond the specific scope of this study, this effort is needed to allow improvement of the overall design wave force process of

which the Morison Equation is a part and to allow the input of accurate water column kinematics to the Morison Equation or its extensions.

Again, the initial thrust of this effort is recommended to be directed toward perceptive utilization of existing and currently being developed technology. Details on this research have been outlined in Section 5.0. The research centers on improved water velocity and acceleration predictions, including three-dimensional effects, near surface effects, near breaking and breaking wave effects, interactions of waves and currents, kinematics characterizations in the time and spectral domains, and simultaneous measurements of kinematics and forces.

In this area of research, it is recognized that it likely will be necessary to conduct additional theoretical, laboratory experimental, and field experimental studies to provide accurate data and fill in gaps in existing technology. This becomes the second thrust of this effort.

Of the many areas concerning appropriate definition and description of wave kinematics, only a few can be adequately studied in laboratory situations or through purely analytic methods. The questions of adequate directional description of wave and wave orbital motions affecting offshore structures, as well as future analytic or statistical methods to better describe these kinematics, all require detailed field measurement studies. An opportunity appears to be avialable to NCEL for instrumenting

an offshore structure and developing a high-quality data set which can be made available to a number of researchers. The immediate opportunity appears to be off the North Carolina coast on the newly-installed Air Combat Maneuvering Range (ACMR) platforms. High-resolution current meters and wave gauges have been developed to a good degree of reliability. Deployment of such instruments, along with automated system controller and data logging equipment, is becoming routine in many offshore areas being developed by commercial interests. Unfortunately, most of the data developed by private industry is either of questionable quality, high expense, or restricted access. On the other hand, were NCEL to undertake a program of systematic data collection from the ACMR platforms, it should be able to design the instrument system, data format, and operating modes in such a way as to provide many investigators, present and future, with a high-quality data set with which to work.

7.4 Recommendation #3

The third area of research recommended for consideration by the Navy is that of basic research on fluid-structure interaction dynamics. This is a long-term research effort intended to lead to development of new analytical models for prediction of wave forces on offshore structures. In its initial thrust, this effort would attempt to better understand and characterize the physics of water flow around structure elements in ocean environments. Both experimental (laboratory and field) and

analytical efforts would be required. The second phase of the effort would be to develop those analytical models which would describe the physics of water flow around structure elements in ocean environments.

7.5 Recommendation #4

The fourth recommendation for consideration by the Navy is that of directing work in these three areas of research. These three areas of needed research are closely related. Given that such research is undertaken, the work would be planned as an overall effort, closely coordinating the efforts, progress, and results in an efficient manner. This work also needs to be carefully coordinated with similar efforts by academic and industrial researchers. Such organized effort is important if the research is to develop significant technology in a reasonable period of time at a reasonable cost.

8.0 CONCLUSIONS

8.1 Scope of Study

In the perspective of design of Naval offshore structures, an assessment of the Morison Equation is provided in this study. Specifically, this study has examined and provided technical comments on the validity and applicability of the basic assumptions upon which the Morison Equation rests, identified those operating regimes where the equation is and is not applicable, and recommended research which could result in improvements and extensions to the Morison Equation, and in development of new methods of analysis that would better fill the need for the Morison Equation.

8.2 Application of the Morison Equation

It is the conclusion of this study that the Morison Equation has proved to be a useful tool or model for computing design wave forces on certain types of offshore structures, particularly of offshore structures that are comprised of elements that are small relative to the waves. Its future use seems assured, since performance of offshore structures designed with the Morison Equation as an ingredient in the design process has been outstanding. The Morison Equation must be viewed as a design-oriented model. Further, it must be viewed as one part of an overall process intended to develop design wave force descriptions on offshore

structures. This study indicates that continued use of the Morison Equation in the design of a given class of Naval offshore structure is warranted.

8.3 <u>Needed Research & Development</u>

Three areas of research and development needs are identified for Navy consideration in this study. These efforts can lead to improvements in the Navy's engineering practice, as well as to improvements on the Morison Equation, or lead to a new formulation or method of analysis filling the need for the Morison Equation.

The first research area identified is the effort to update the Navy's wave force design guideline in light of the current improvements and extensions made to the original Morison Equation. An associated primary research objective is to develop a Unified Wave Force Formulation that will represent an orderly and systematic design procedure or guideline which fully recognizes the complex components of the general problem of designing Naval offshore structures. The second research area identified is the effort to improve descriptions of the sea state and associated water column kinematics. The third research effort identified is the need to improve basic research on fluid-structure interaction dynamics.

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8.4 Justification for Research

Research to improve the application of the Morison Equation can be justified along two fundamental lines of reasoning:

1. In the 30 years since introduction of the Morison Equation, the Naval offshore structures have been designed for and installed in progressively more severe environments, in both water depth and sea state intensity terms. A better and more reliable wave force formulation is needed to assure adequate and acceptable structural performance;
2. With the new development of more expensive offshore structures, a better and more exact wave force formulation is needed to reduce the sources of unwarranted conservatisms in the design process and thus reduce the costs of the structures.

9.0 CREDITS

This investigation is sponsored by the Civil Engineering Laboratory of Naval Construction Battalion Center, under contract No. N683-5-80-C-0007. The project team includes Ngok Lai, Alan Niedoroda, and Bob Bea. The reviews and comments from Mr. Tom Ward (Naval Civil Engineering Laboratory), Prof. Leon Borgman (Univ. of Wyoming), Prof. Charles Dalton (Univ. of Houston), Prof. Bob Dean (Univ. of Delaware), and Prof. Turgut Sarpkaya (Naval Postgraduate School) are greatly appreciated.

Alan W. Niedoroda
Sr. Oceanographer

Ngok W. Lai
Project Engineer

R. G. Bea, Chief
Ocean Engineering Division

REV:GLB

FIGURES

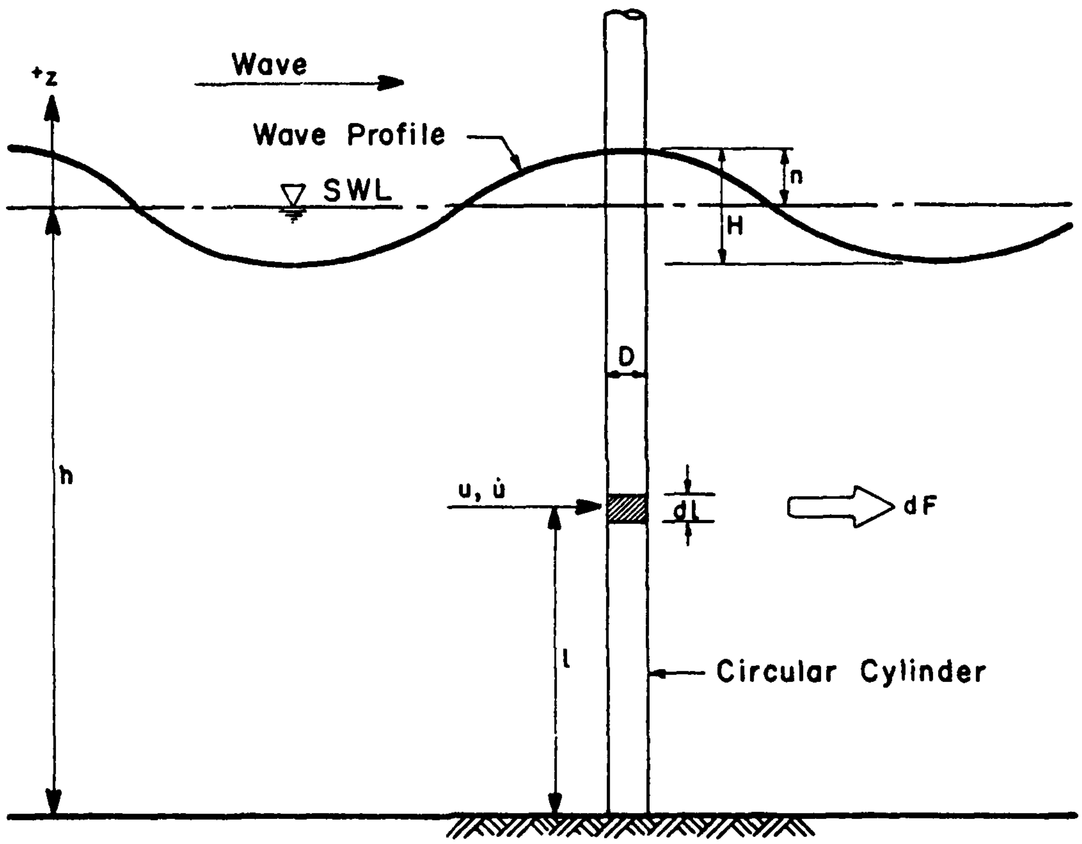

FIG. 2.1 DEFINITION SKETCH

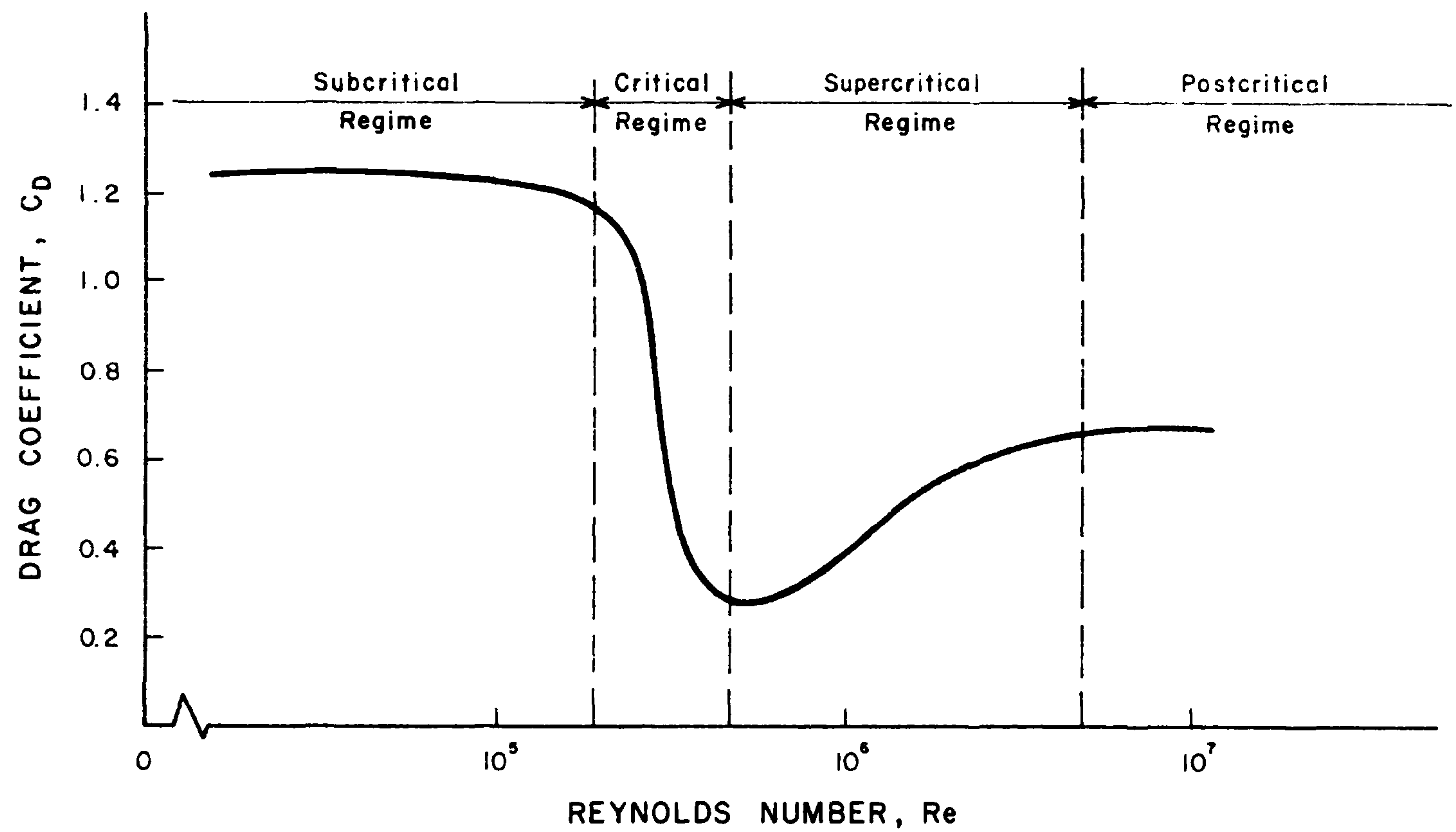

FIG. 3.1 VARIATION OF DRAG COEFFICIENT WITH REYNOLDS NUMBER FOR A SMOOTH CYLINDER IN STEADY UNIFORM FLOW

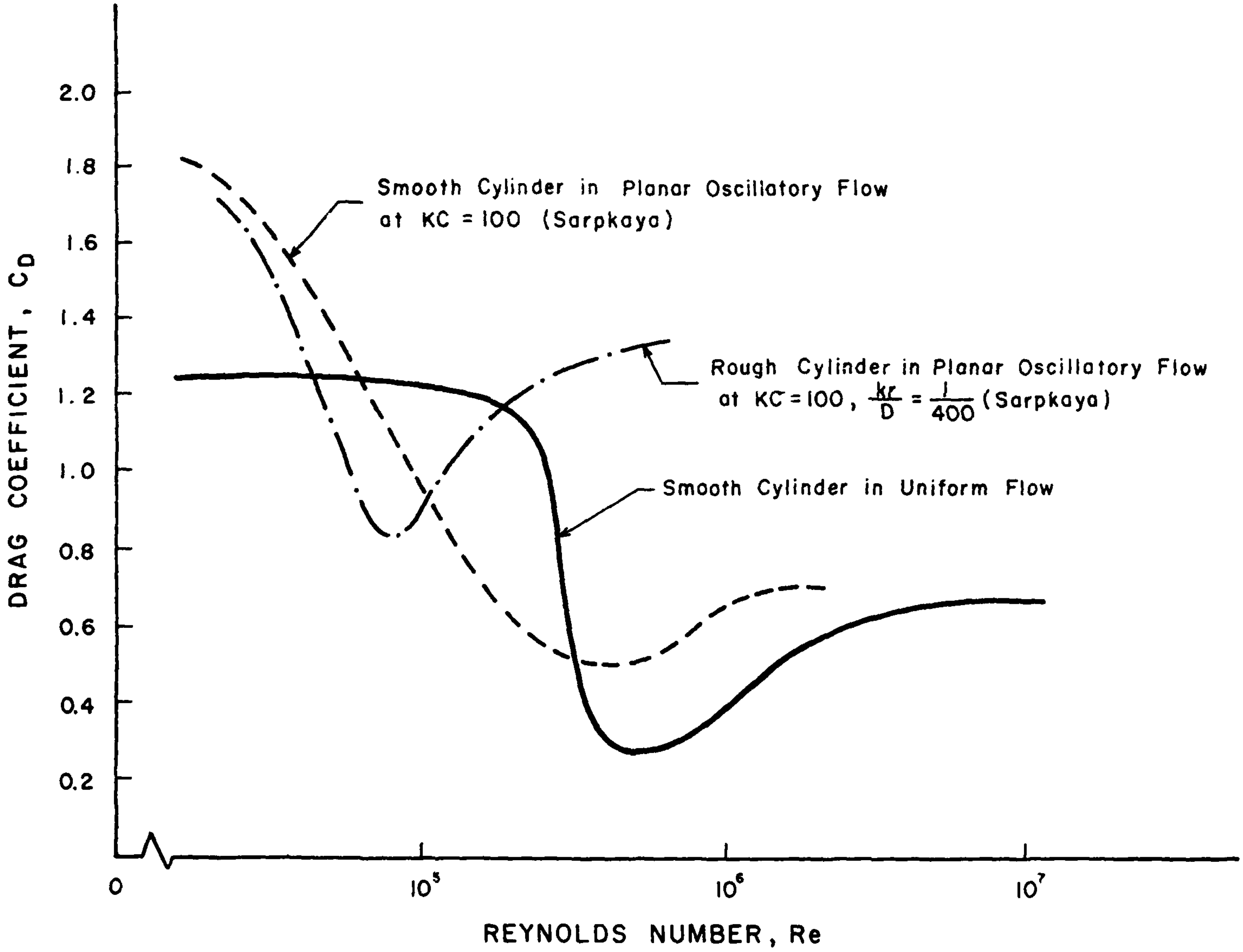

FIG. 3.2 COMPARISON OF THE RELATIONS OF DRAG COEFFICIENT WITH REYNOLDS NUMBER IN UNIFORM FLOW AND PLANAR OSCILLATORY FLOW

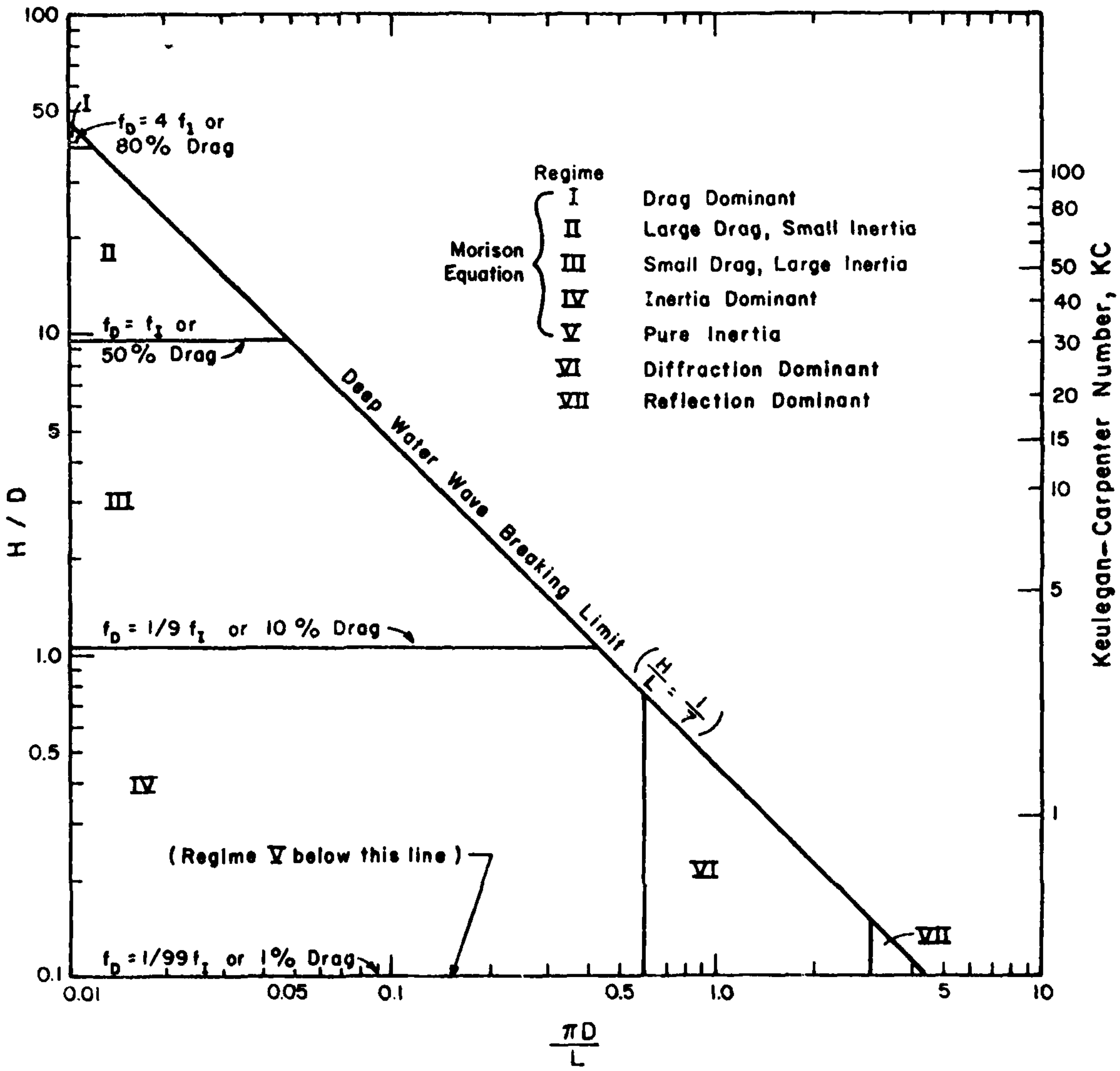

FIG. 3.3(a) WAVE LOADING REGIMES NEAR WATER SURFACE

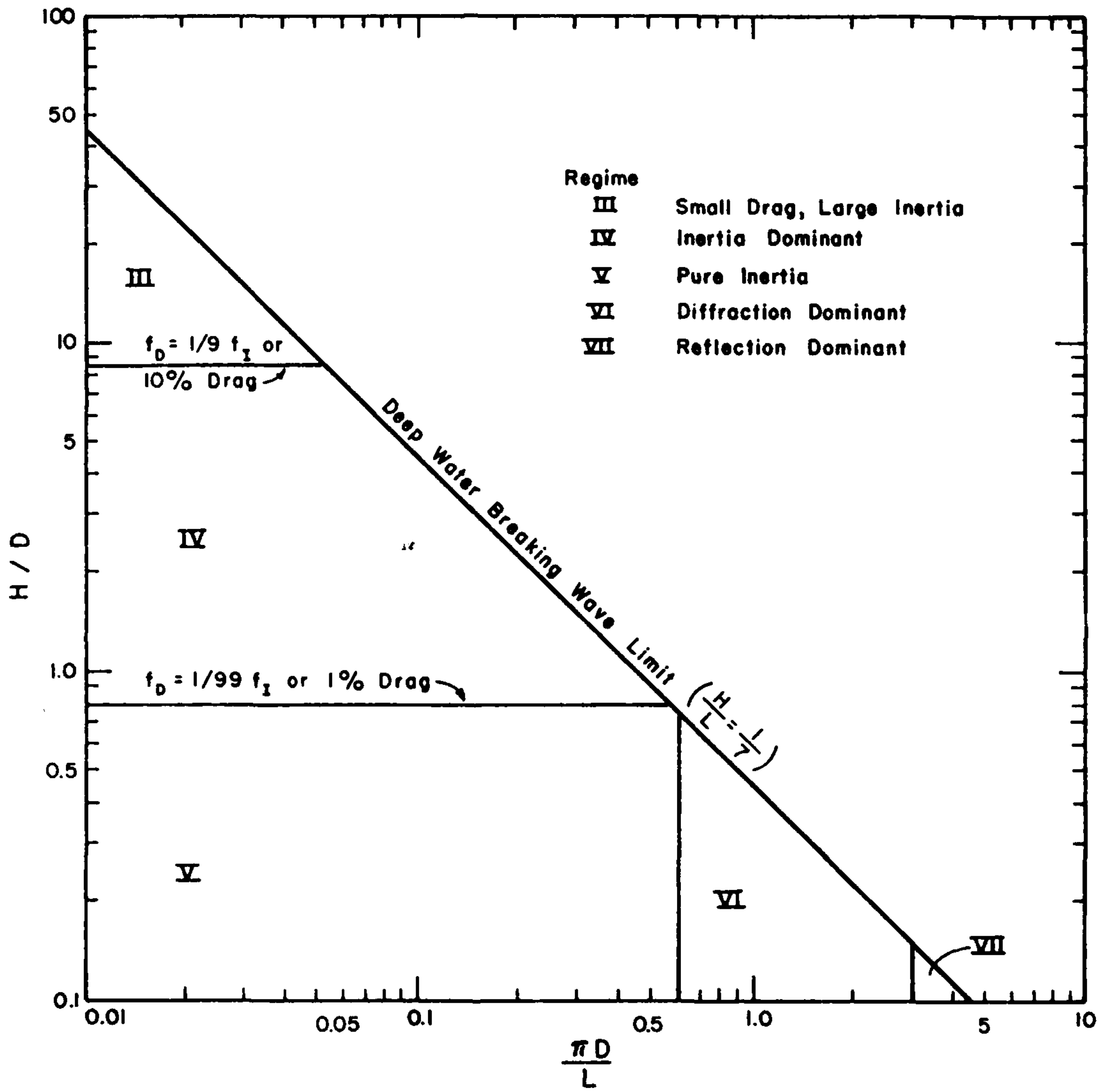

FIG. 3.3(b) WAVE LOADING REGIMES AT 150 FT BELOW WATER SURFACE FOR A 30 FT WAVE HEIGHT

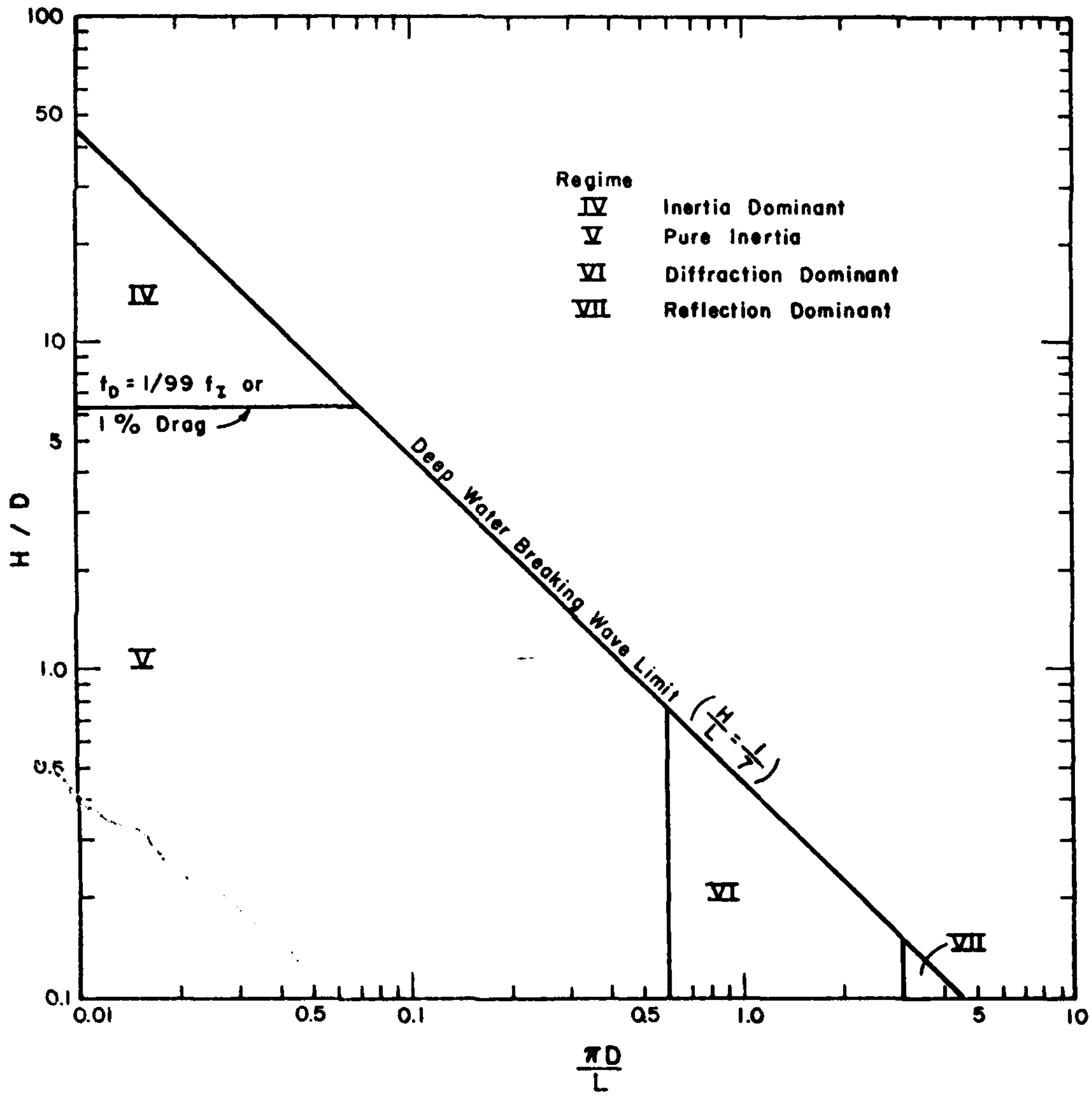

FIG. 3.3(c) WAVE LOADING REGIME AT 300 FT BELOW WATER SURFACE FOR A 30 FT WAVE HEIGHT

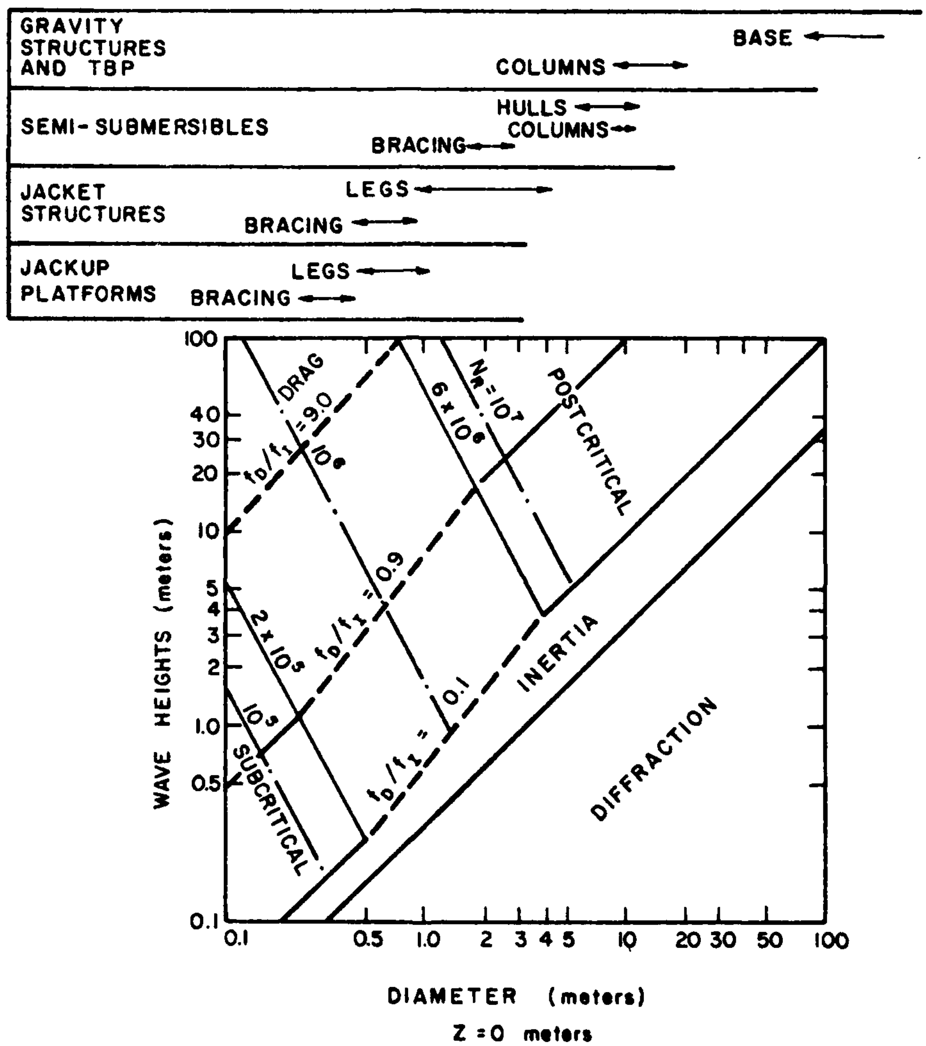

FIG. 3.4 COMPARATIVE IMPORTANCE OF DIFFERENT LOADS FOR DIFFERENT WAVE AND MEMBER GEOMETRIES (ADAPTED FROM HOGBEN, 1976)

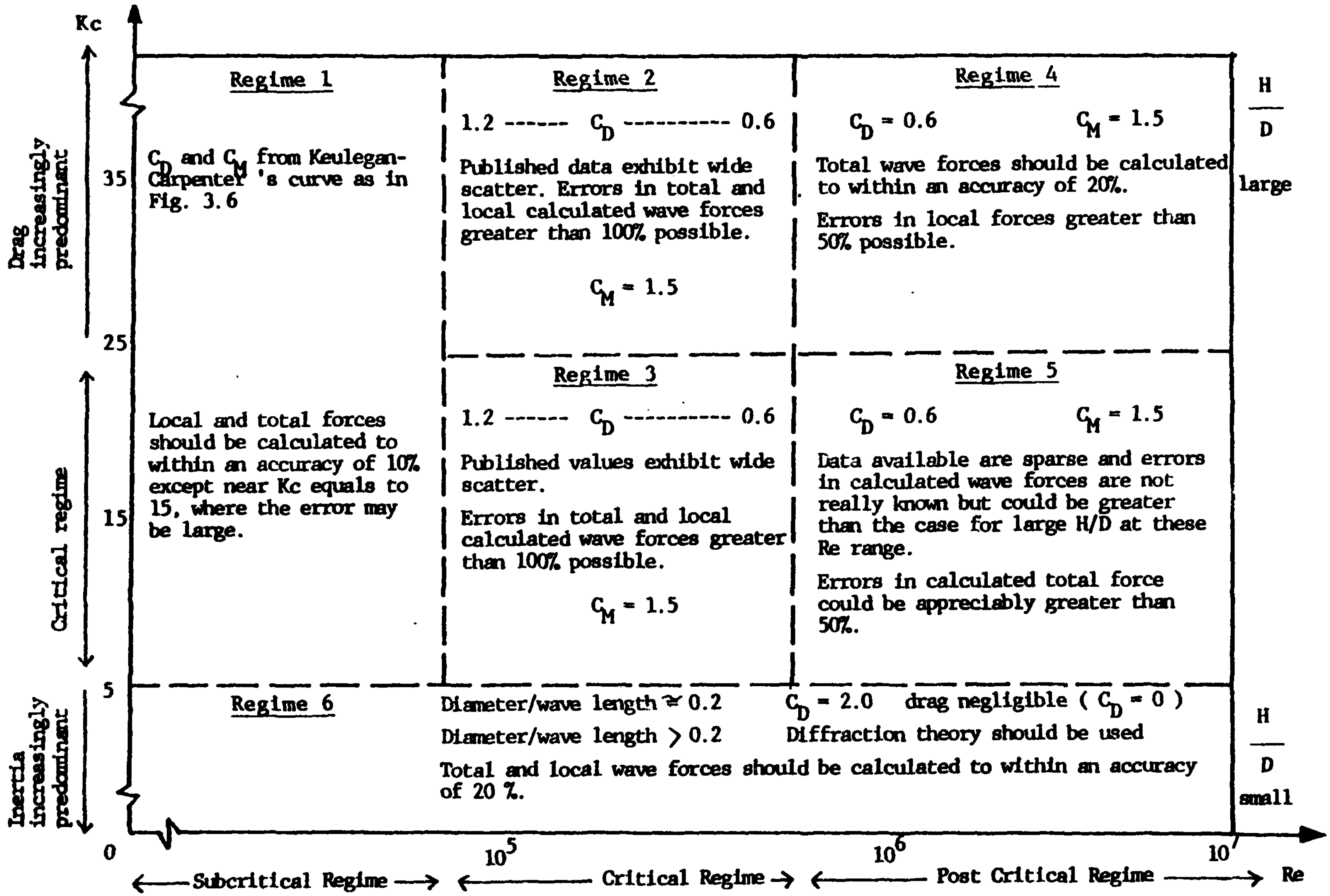

FIG. 3.5 SUMMARY OF SUGGESTED VALUES OF C_D AND C_M AS FUNCTIONS OF REYNOLDS NUMBER AND KEULEGAN-CARPENTER NUMBER FOR SMOOTH, VERTICAL SURFACE PIERCING CIRCULAR CYLINDERS (Adapted from Hogben,et al. 1977)

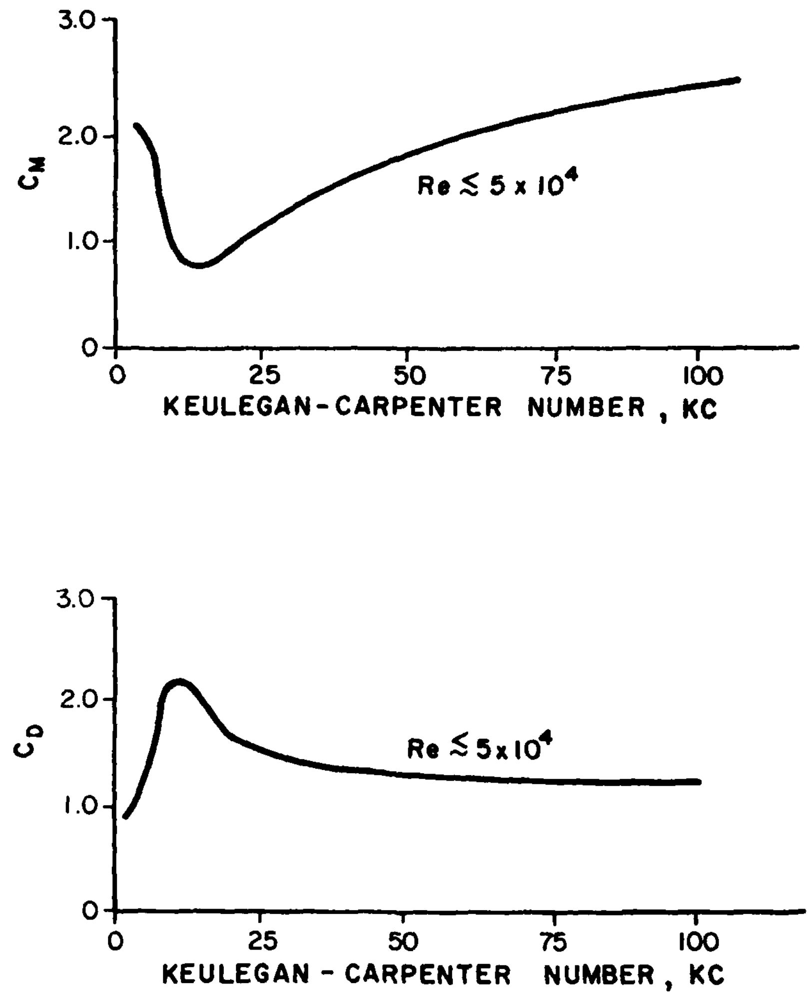

FIG. 3.6 SUGGESTED VALUES OF INERTIA AND DRAG COEFFICIENTS AT SUBCRITICAL REYNOLDS NUMBER FOR THE WAVE FORCE NORMAL TO THE AXIS OF A SMOOTH CIRCULAR CYLINDER (KEULEGAN AND CARPENTER, 1958)

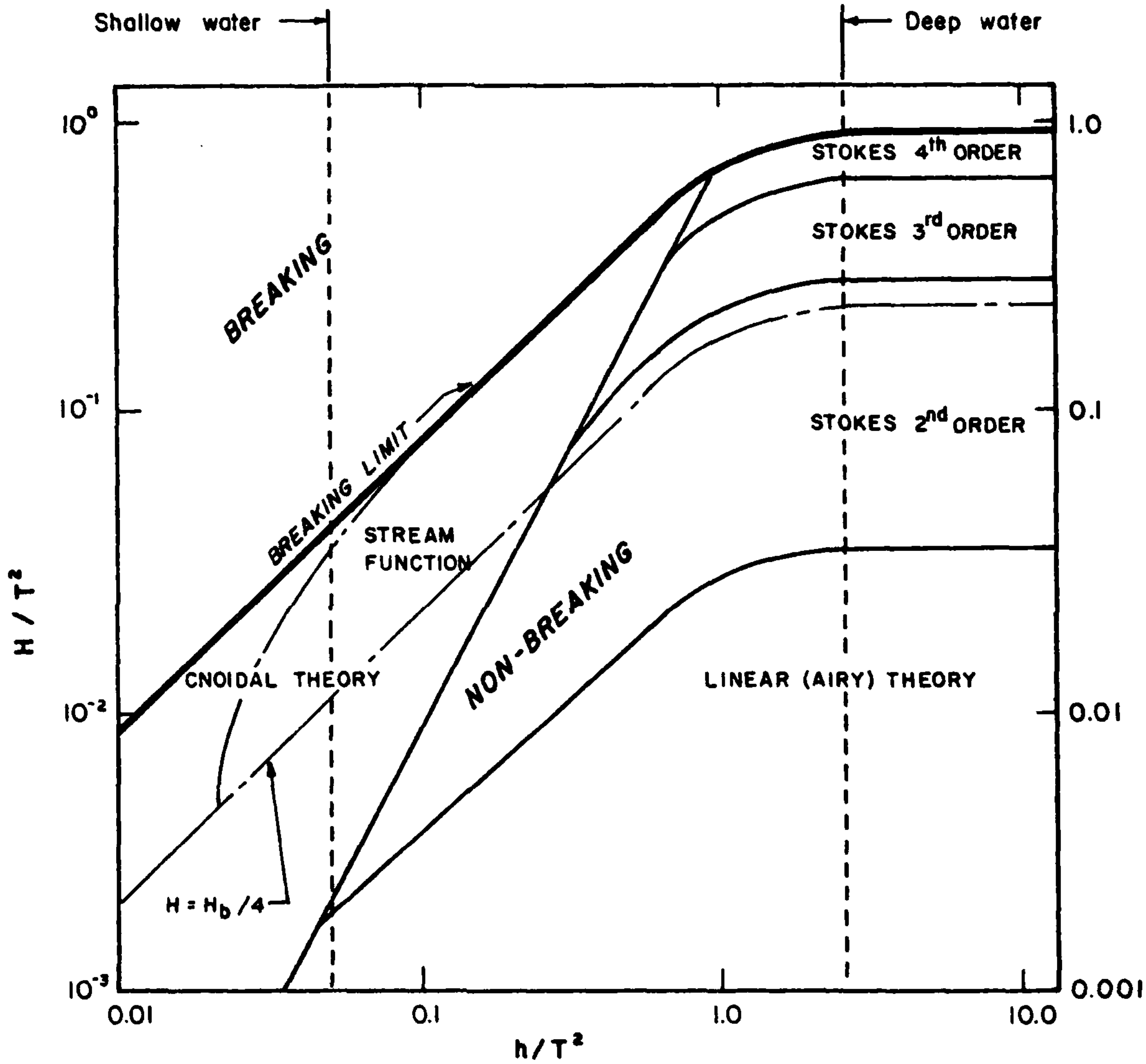

FIG. 3.7 REGIONS OF VALIDITY FOR VARIOUS WAVE THEORIES WITH EXPERIMENTAL VALUES (DEAN AND LE MEHAUTE, 1970)

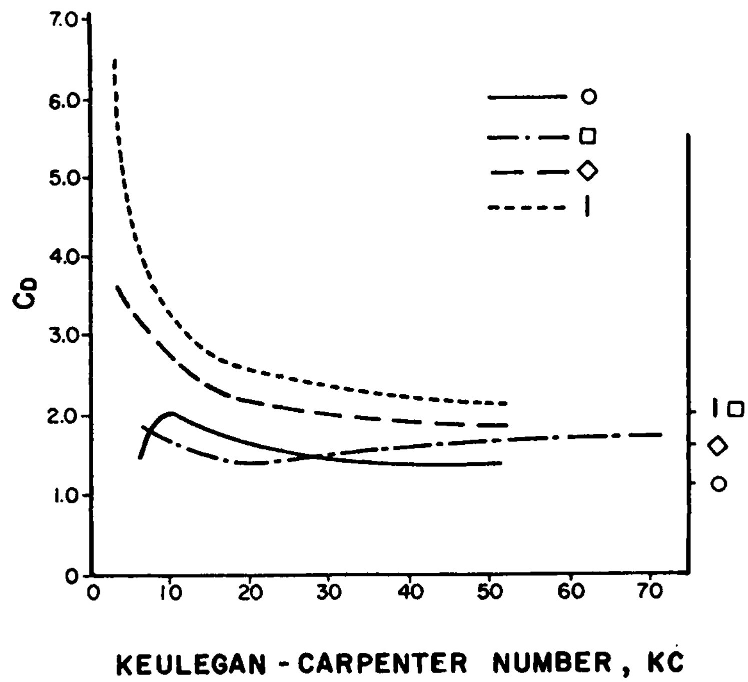

FIG. 4.1 VARIATIONS OF DRAG COEFFICIENT WITH KEULEGAN-CARPENTER NUMBER FOR FOUR BODY SHAPES (BEARMAN,ET AL. 1979)

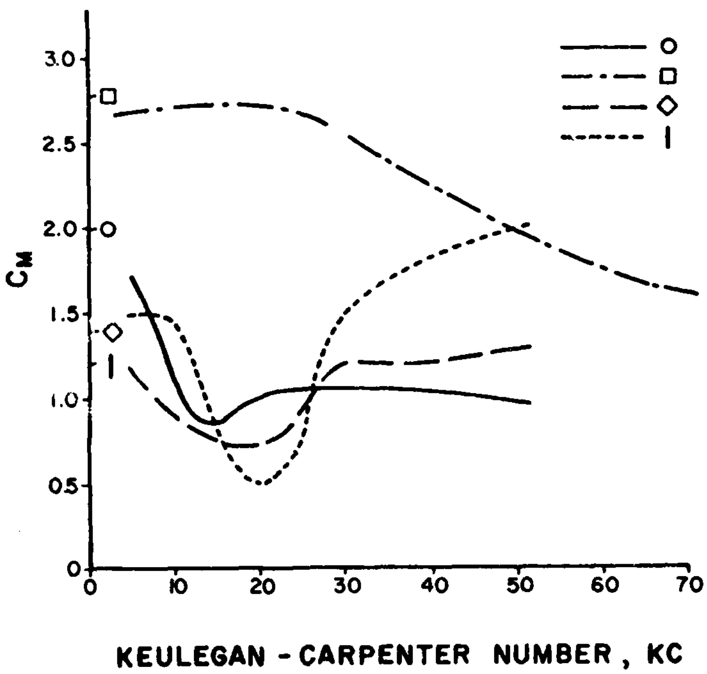

FIG. 4.2 VARIATION OF INERTIA COEFFICIENT WITH KEULEGAN-CARPENTER NUMBER FOR FOUR BODY SHAPES (BEARMAN,ET AL. 1979)

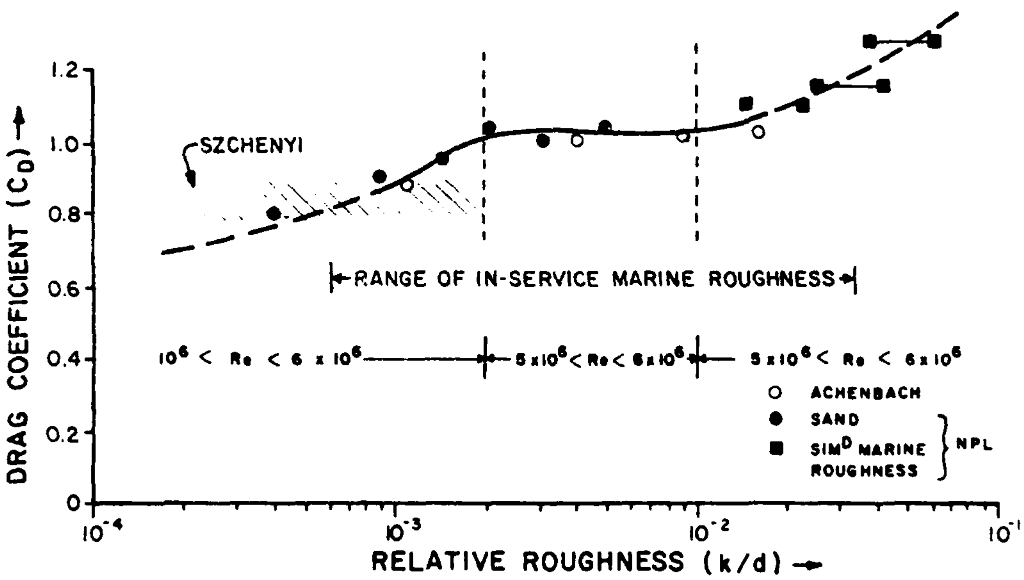

FIG. 4.3 EFFECT OF RELATIVE ROUGHNESS HEIGHT ON THE POST-CRITICAL LEVEL OF DRAG COEFFICIENT IN UNIFORM INCIDENT FLOW (HOGBEN,ET AL. 1977)

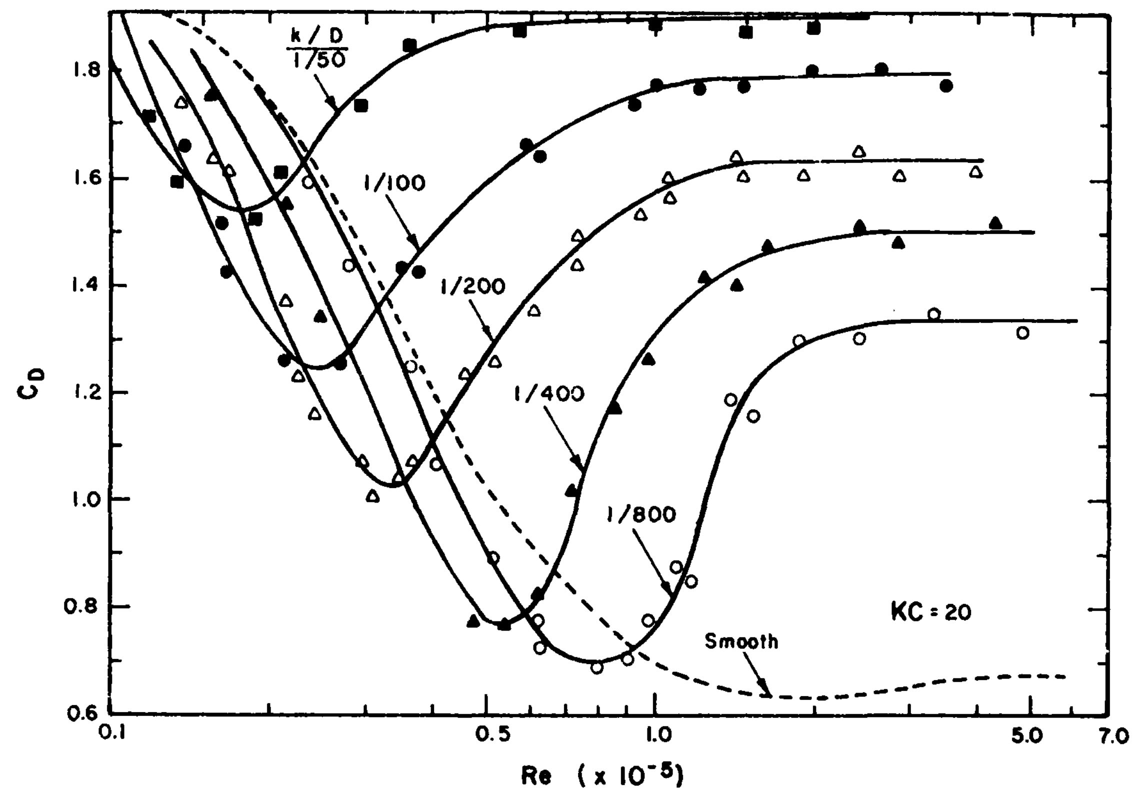

FIG. 4.4 EFFECT OF SURFACE ROUGHNESS ON THE DRAG COEFFICIENT IN PLANAR OSCILLATORY INCIDENT FLOW (SARPKAYA, 1976)

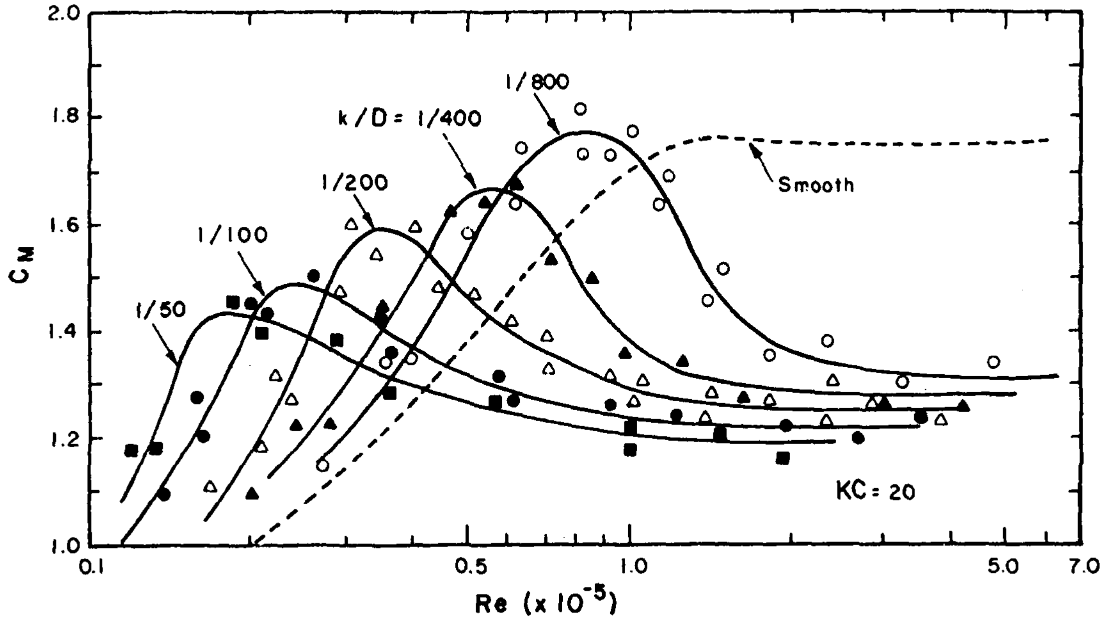

FIG. 4.5 EFFECT OF SURFACE ROUGHNESS ON THE INERTIA COEFFICIENT IN PLANAR OSCILLATORY INCIDENT FLOW (SARPKAYA, 1976)

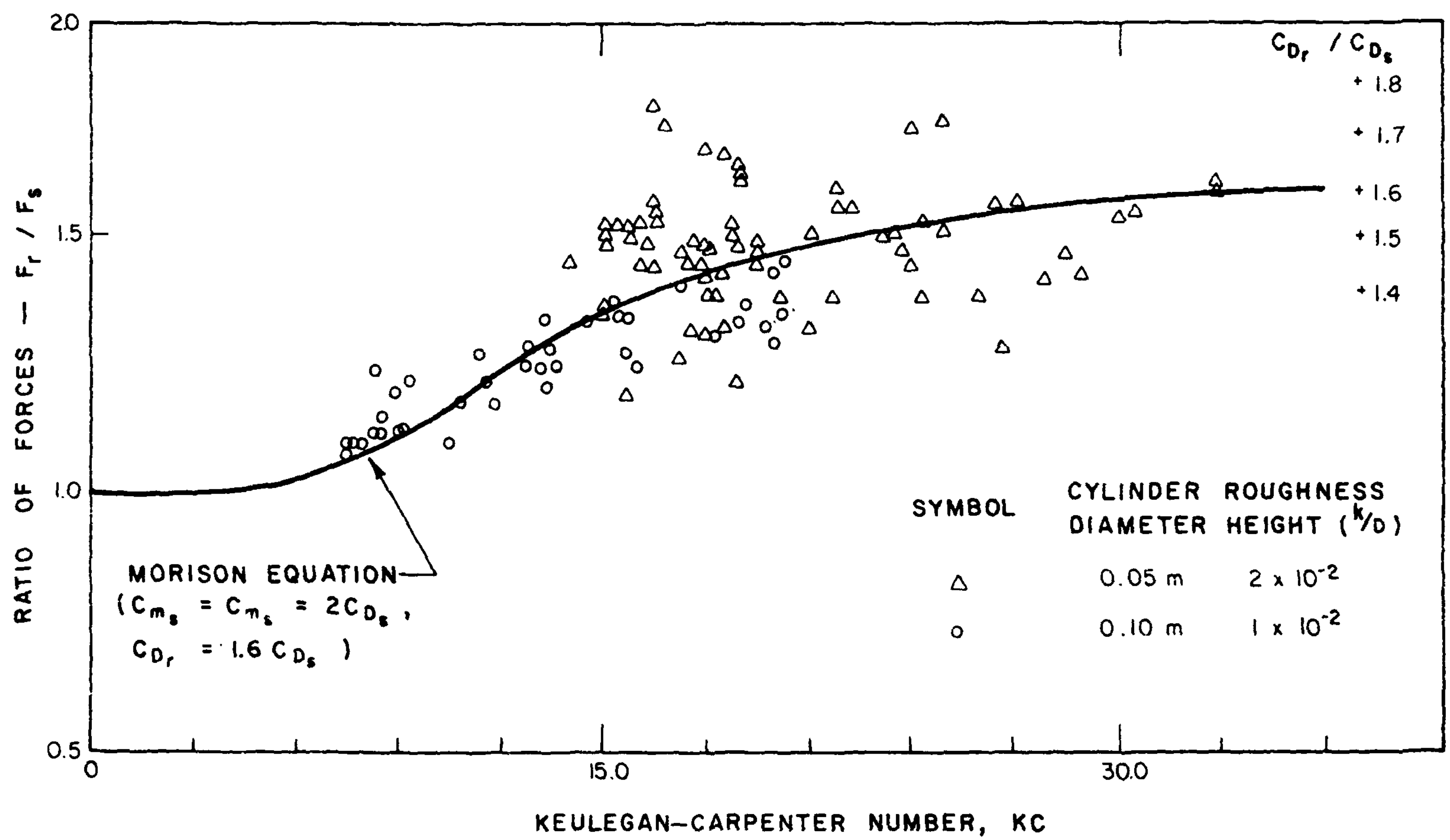

FIG. 4.6 DEPENDENCE OF RATIO OF FORCES ON ROUGH AND SMOOTH CYLINDERS ON KEULEGAN-CARPENTER NUMBER (MATTEN, 1977)

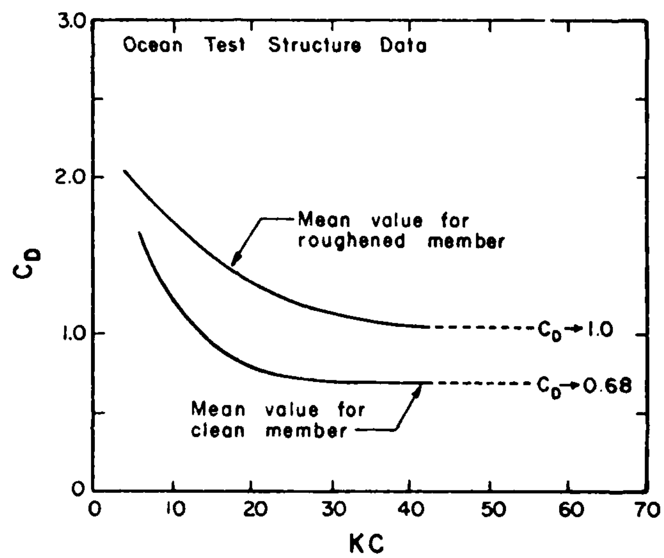

FIG. 4.7 COMPARISONS OF DRAG COEFFICIENTS FOR SMOOTH AND BARNACLE-ENCRUSTED CYLINDERS (HEIDEMAN, ET AL. 1979)

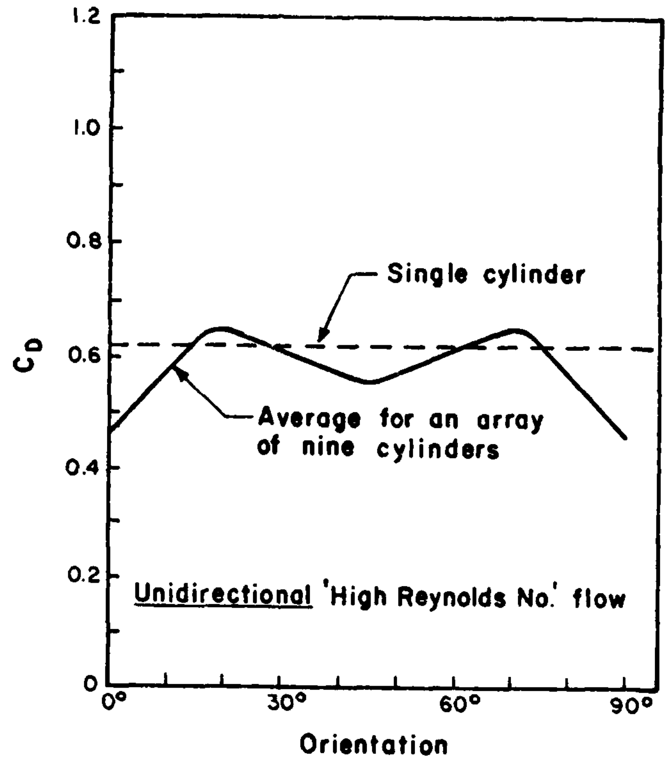

FIG. 4.8 AVERAGE DRAG COEFFICIENT FOR CYLINDERS IN A 3 x 3 ARRAY WITH EQUAL SPACING FOR FOUR DIAMETERS (PEARCEY, 1975)

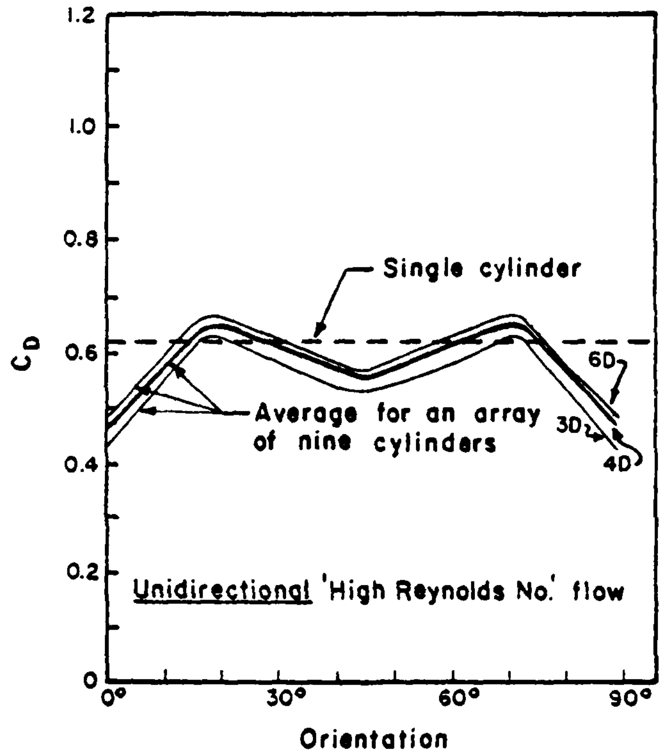

FIG. 4.9 AVERAGE DRAG COEFFICIENT FOR CYLINDERS IN A 3 x 3 ARRAY: EFFECT OF SPACING (PEARCEY, 1975)

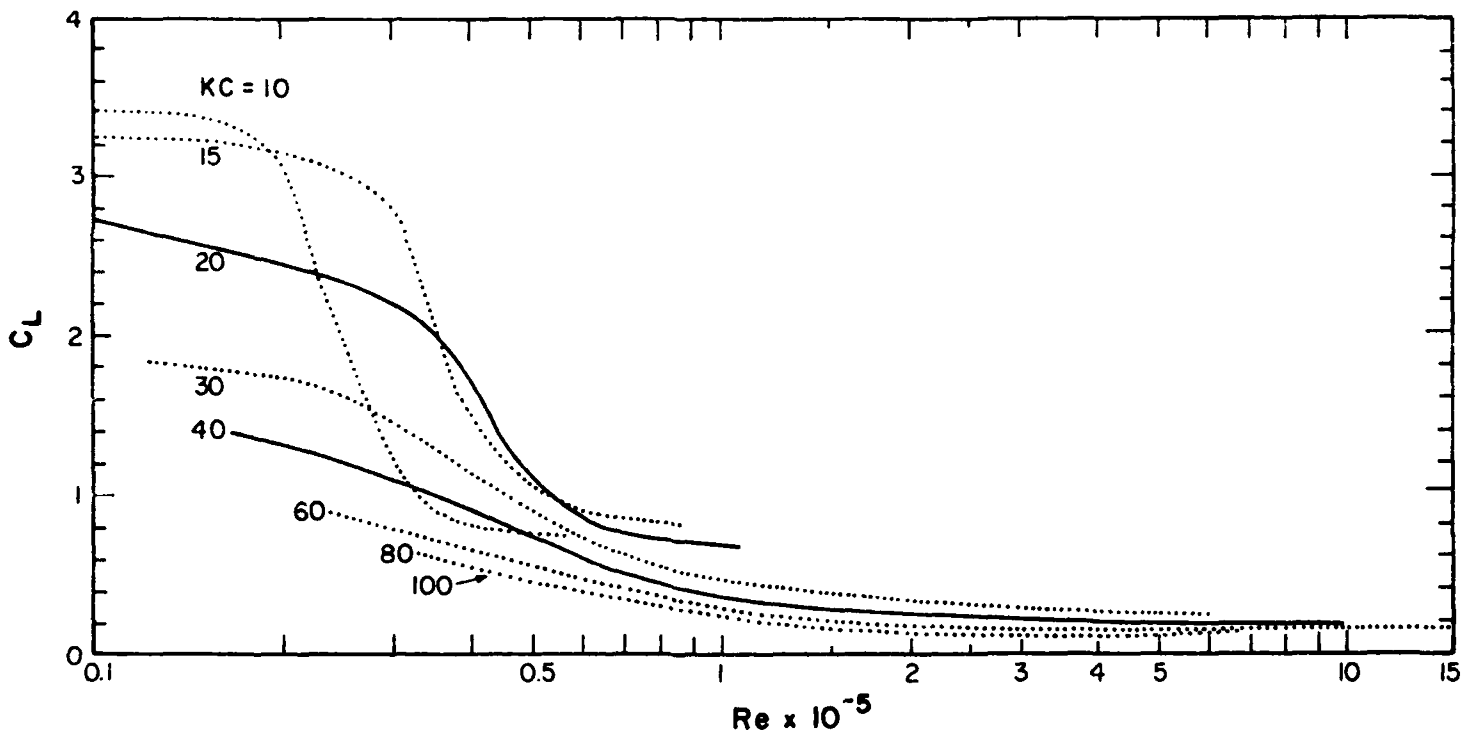

FIG. 4.10 MAXIMUM LIFT COEFFICIENT VS. REYNOLDS NUMBER FOR VARIOUS KEULEGAN-CARPENTER NUMBER (SARPKAYA, 1976b)

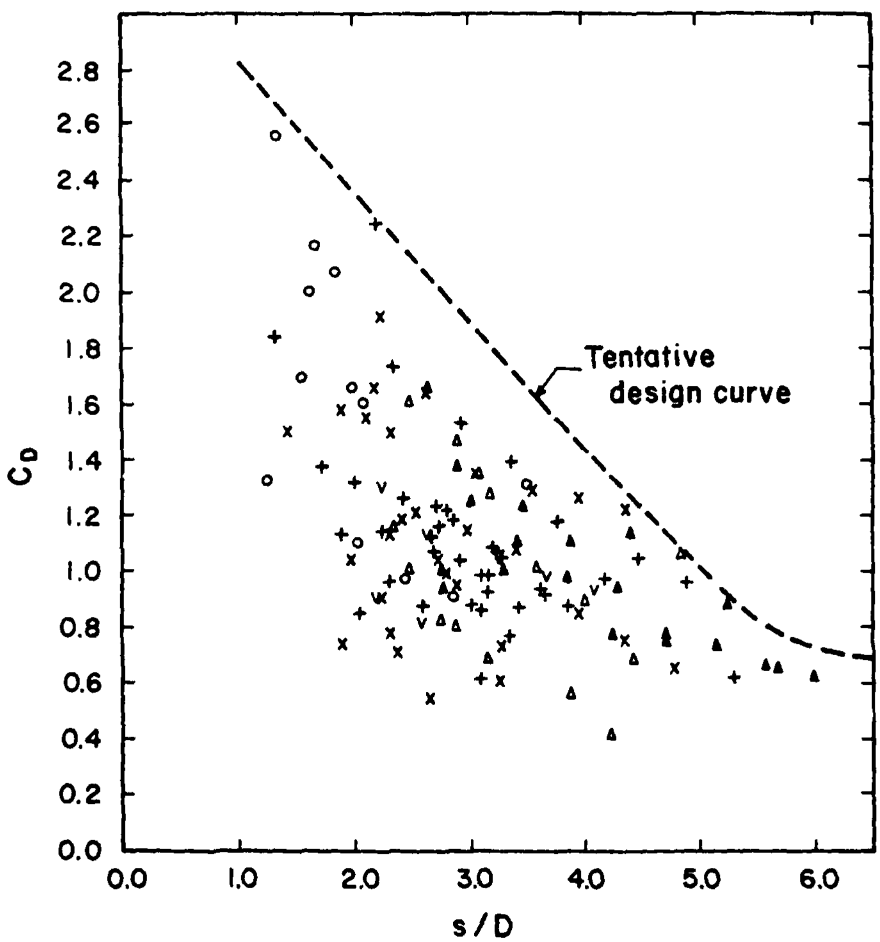

FIG. 4.11 DRAG COEFFICIENT DEPENDENCE ON RELATIVE DISTANCE OF WATER PARTICLE TRAVEL (GRACE, ET AL. 1976)

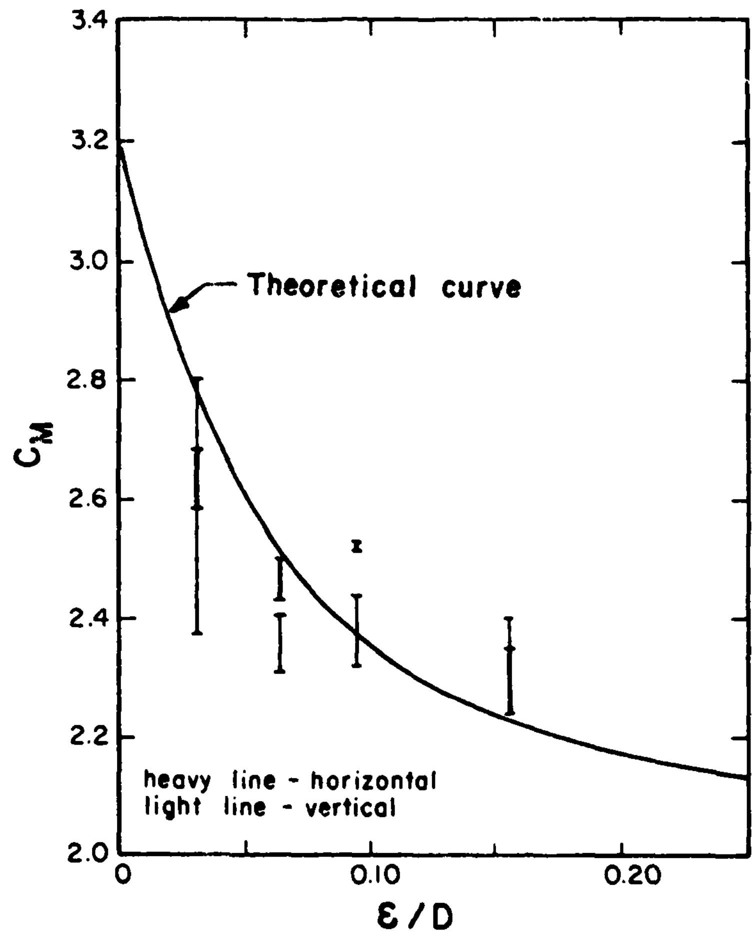

FIG. 4.12 90% CONFIDENCE INTERVALS FOR INERTIA COEFFICIENT DETERMINATIONS W.R.T. RELATIVE CLEARANCE FROM BOTTOM (GRACE, ET AL. 1976)

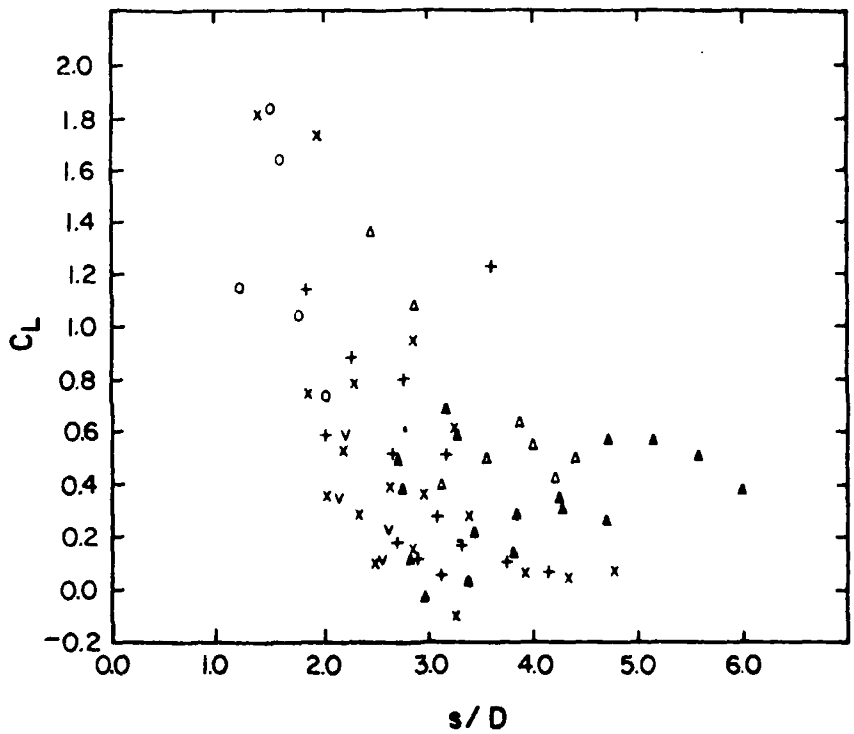

FIG. 4.13 LIFT COEFFICIENT VARIATION WITH RELATIVE DISTANCE OF WATER PARTICLE TRAVEL (GRACE, ET AL. 1976)

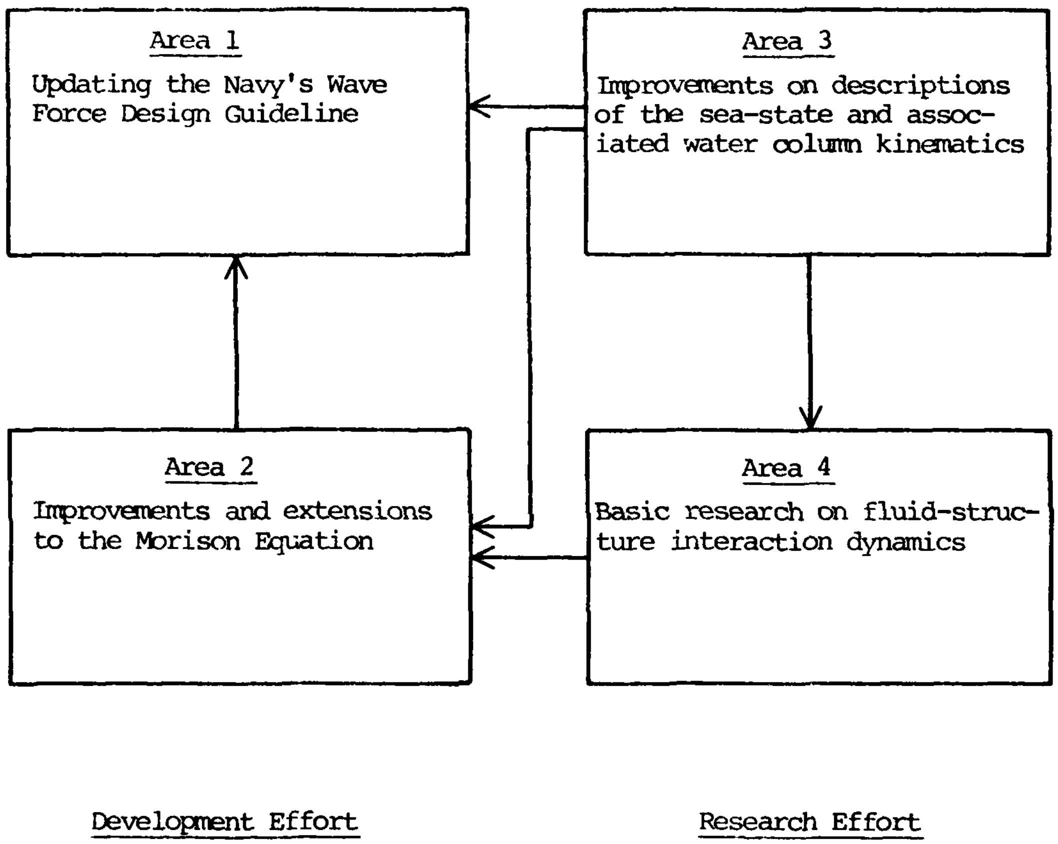

FIG. 5.1 RESEARCH AND DEVELOPMENT AREAS IDENTIFIED FOR IMPROVING WAVE FORCE COMPUTATIONS ON NAVAL OFFSHORE STRUCTURES

TASK 1	Better characterization of wave forces on structural elements	1. Surface roughness 2. Noncircular cylindrical sections 3. Vortex-induced lift forces 4. Near-surface wave slamming 5. Near-surface cyclic buoyancy 6. Inclined members 7. Vibrating and compliant structure motions
TASK 2	Better characterization of complex assemblages of structural elements	1. Mutual interference of conglomeration of multiple members 2. Surface roughness 3. Noncircular cylindrical sections 4. Vortex-induced lift forces 5. Near-surface wave slamming 6. Near-surface cyclic buoyancy 7. Inclined members 8. Vibrating and compliant structure motions
TASK 3	Temporal characterization of wave forces	1. Time-wise and spatial variations of fluid flow conditions 2. Variations of force coefficients throughout wave cycle 3. Fluid-structure dynamic response
TASK 4	Spectral characterization of wave forces	1. Spectral wave force dynamic analysis 2. Spectral wave force fatigue analysis 3. Directional wave force spectra analysis 4. Nonlinear response
TASK 5	Probabilistic characterization of wave forces	1. Statistical descriptions of wave force parameters 2. Directional wave spreading descriptions 3. Joint probability distribution descriptions
TASK 6	Better quantification of force coefficients	1. Force coefficients for complex conditions 2. Force coefficients for large Reynolds number range 3. Force coefficients for different wave force analysis approaches 4. Systematic distillation of existing wave force data

FIGURE 5.2 RESEARCH NEEDS FOR IMPROVING AND EXTENDING THE MORISON EQUATION

1. Better Characterization of the Wave Field

   1. Velocities and accelerations
   2. Kinematics of breaking waves
   3. Nonlinear wave-current interactions
   4. Short-crested and directional waves

2. Better Characterization of Water Column Motions

   1. Ocean current and current profile
   2. Effects of density stratification
   3. Effects of internal waves

3. Interaction Effects

   1. Nonlinear interactions of relative motions
   2. Boundary layer interactions

FIG. 5.3 RESEARCH NEEDS TO IMPROVE THE DESCRIPTION OF OCEAN KINEMATICS

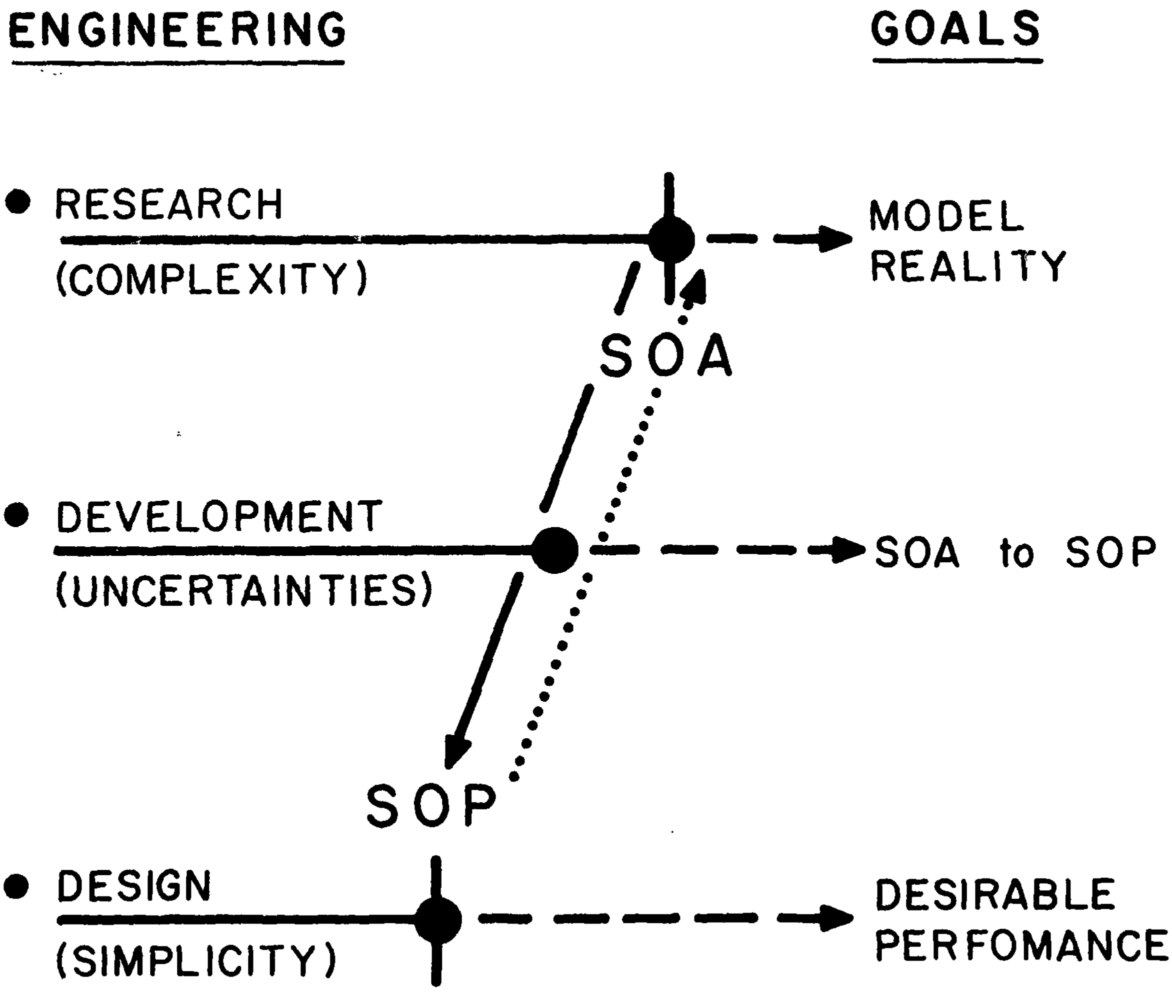

FIG. 6.1 GENERAL FORMS OF RESEARCH ACTIVITIES

APPENDIX A

Appendix A

(BSRA, 1976)

Summary of literature giving explicit C_M and C_D values (the C_M and C_D force, and R_e and K_c have been evaluated using the maximum horizontal wave particle values given are applicable to the calculation of the horizontal component of wave orbit velocity at the still water level, unless otherwise stated).

AUTHOR	LOCATION	SEA STATE	STRUCTURE	K_c and R_e	C_D	C_M	Reliability/wave theory
Reid (1958)	Gulf of Mexico	Small amplitude sea waves $2<H<4$ ft $3<T<5$s Wind speed 10-30 mile/h Current 0.5 - 0.7 ft/s at surface	Vertical cylinder clamped above water with other end loose D = 8.625 in.	$K_c=10-20$, $R_e=10^5-2\times10^5$	0.53 Standard deviation 0.20	1.47 Standard deviation 0.36	Measured wave force records and those calculated using constant mean C_M and C_D values given showed good agreement; linear spectral technique was used, with the effect of a current considered in the analysis. Inertial force was about double the drag force. Structural vibration was observed and allowed for in the analysis.
Wiegel et al (1957)	Pacific coast of California at Davenport	Storm waves $5<H<20$ ft $9<T<17$s $45<d<50$ ft Wind waves superimposed on the swell.	Vertical cylinders D=6.625 in., 1.0, 2.0, 5.0 ft. with test section at various depths	$K_c=8-40$, $R_e=3\times10^4-9\times10^5$, evaluated at test section levels using maximum Airy orbital velocity.	0.1-5.0 Extremes of scatter. Average about 0.5-0.7 at $R_e=5\times10^5$, increasing to 1.0 and above at smaller R_e	0.7-6.0 Extremes of scatter. 2.5 given as mean value of a Gaussian distribution	Local forces, calculated using linear wave theory and average values of C_M and C_D differed from measured forces by up to about 100%. The large scatter was attributed to roughness, turbulence, wind waves and shallow water effects. Effect of a current was not considered. Structural vibration, which resulted in fatigue failure, was observed.
Wilson (1965)	Gulf of Mexico	Confused sea of two wave trains Observed H and T $3<H<8$ ft $5<T<8$s d=38 ft Wind speed 18 knots Current 0.55 ft/s at surface	Vertical cylinder suspended in the water D=2.5 ft	$K_c=5-15$, $R_e=3\times10^5-10^6$	(a)0.32 Current not considered (b)0.60 Current considered (c)2.75 Current considered and phase correction between force and wave record included (d) 1.79 Best results from (b) and (c) averaged	(a) 1.53 Current not considered (b) 1.54 Current considered (c) 1.36 Current considered and phase correction between force and wave record included (d) 1.53 Best results from (b) and (c) averaged	Large scatter in C_D and C_M values from different wave force record analyses; correlation between calculated and measured force varied from poor to very good for individual records. A linear spectral method of data analysis was used. C_D values were *significantly* affected by current; C_M appeared to be unaffected by the current. Structural vibration, which resulted in fatigue failure, was observed.

AUTHOR	LOCATION	SEA STATE	STRUCTURE	K_c and R_e	C_D	C_M	Reliability/wave theory
Bretschneider (1967)	Calif. coast, Davenport	Storm waves $5<H<20$ ft $9<T<17$ s $45<d<50$ ft	Vertical cylinders $D = 1,2$ ft	$K_c=8$-40, $R_e=10^5$-10^6, evaluated using linear theory values beneath the wave crest, considering variation with depth	0.4-1.5 Higher values more probable	2-5 Lower values more probable	C_D at 1% level=0.5±20%, C_M values were unsatisfactory. Probabilistic approach considering peak drag and inertial forces and linear wave theory
Aagard and Dean (1969)	Gulf of Mexico wave force projects I and II	Hurricane storm waves $6<H<40$ ft $6<T<17$ s $d = 30, 100$ ft	Vertical cylinders $d = 30$ ft $D = 1,2,3,4$ ft $d = 100$ ft $D = 3.7$ ft	$K_c=15$-50, $R_e=10^4$-10^7 evaluated using Stokes fifth order theory values beneath the wave crest, considering variation with depth	1.2-0.5 decreasing with R_e. For in-line force	1.33 For in-line force	Calculated forces averaged over H,T,d agreed to within 10% of measured total forces. Calculated and measured local force maxima agreed to within 50%. Effects of currents not considered. Stream function wave theory to be used with wave force evaluation technique given
Evans (1969)	Gulf of Mexico wave force projects I and II	Project I $10<H<20$ ft $6<T<10$ s $d=30$ ft Project II $25<H<45$ ft $10<T<17$ s $d=100$ ft	Vertical cylinders $D = 1,2,3,4$ ft Vertical cylinder $D = 3.7$ ft	$K_c=20$-50, $R_e=10^5$-2×10^6, evaluated using Stokes fifth order theory wave crest and trough values. $K_c=10$-80, $R_e=10^5$-5×10^6, evaluated using Stokes fifth order theory values beneath the wave crest, considering variation with depth	0.5 0.58 Standard deviation 0.33	1.5 1.76 Standard deviation 1.06	Wave force project I. Calculated total forces were generally within 10% of the measured forces, and usually conservative Wave force project II. C_M and C_D were averaged over H, T, d but varied appreciably with H, T, d. Agreement between measured local forces and those calculated using local C_M and C_D values was quite good. Maximum total forces calculated using mean C_M and C_D values generally agreed to within 10% of measured forces and were usually conservative Wave force projects I and II. Wave theory to be used depends on wave characteristics, and is one of Chappelier, Stokes fifth order, linear or McCowan, to be used in the wave force evaluation technique given. Effects of currents were not considered
Grace & Casciano (1969)	Hawaii coast	Small sea waves $1.7<H<5.6$ ft $11<T<16$ s $d=25$ ft	Sphere on sea bed D=8 in	$K_c=8$-60, $R_e=6 \times 10^4$-9×10^5, evaluated using Stokes third order theory maximum orbit velocity at the centre of the sphere.	0.7	1.2	Peak forces calculated using Stokes third order wave theory were generally within 25% of the measured forces. The wave force was drag dominant; a constant value of C_M was assumed. The same H, T for different waves gave C_D values differing by over 100%.

AUTHOR	LOCATION	SEA STATE	STRUCTURE	K_c and R_e	C_D	C_M	Reliability/wave theory
Wheeler (1969)	Gulf of Mexico wave force project II	Hurricane storm waves $20<H<40$ ft $10<T<17$ s $d=99$ ft	Vertical cylinder D = 3.7 ft	$K_c=24-65, R_e=2.5\times10^6-5.0\times10^6$	0.6 Smaller (≈0.4) at surface	1.[illegible]-2.0 Varying with depth	Measured and calculated maximum local forces differed by up to 40% in high waves. A linear spectral method of data analysis was used. Effect of currents was not considered.
Hudspeth et al (1974)	Gulf of Mexico wave force projects I and II	Hurricane storm waves $10<H<40$ ft $6<T<17$ s $d=33$, 100 ft	Vertical cylinders d = 30 ft D = 1,2,3,4 ft d = 100 ft D = 3.7 ft	$K_c=10-70, R_e=10^4-10^7$, evaluated using Stokes fifth order theory values beneath the wave crest, considering variation with depth.	1.2-0.5 decreasing with R_e	1.1	Methods and results of data analysis using linear spectral wave theory and stream function wave theory were compared. The standard deviation between measured and calculated forces was smallest for the C_M and C_D values given using the stream function theory
Kim and Hubbard (1975)	Bass Straits, Australia	Small amplitude sea waves $2.55<H<9.87$ ft (significant height) $4.35<T<8.70$ s (dominant period) d = 7.25 ft at test section. Current = 1 ft/s	Vertical cylinder D = 12.75 in.	$K_c=12-80, R_e=2.5\times10^5-8.0\times10^5$, evaluated using measured velocity at test section	0.61 Standard deviation 0.24	1.2 Standard deviation 0.22	C_D was stated to be constant and independent of R_e above $R_e=2\times10^5$. Agreement between measured and calculated force was good in the drag dominated part of the wave cycle, and fair in the inertia dominated part. Orbit velocity was measured.
Heideman, Olsen and Johansson (1979)	Gulf of Mexico, Ocean Test Structure	Storm waves $9<H<24$ ft $6<T<12$ s water depth, 66 ft	Vertical cylinders D = 16 in 1/5 scale prototype	$K_c=5-48, R_e=2\times10^5-8\times10^5$ Evaluated by measured velocity at test section.	1.5-0.68 mean values for clean members, decreasing with K_c. 1.8-1.0 mean values for fouled members, decreasing with K_c	1.51-1.65 mean values for clean members. 1.25-1.43 mean values for fouled members	Wave force coefficients calculated based on measured kinematics with a current meter 4.67 ft away from force transducer. Large scatter at low K_c, but decreases considerably at high K_c. Agreement between calculated and measured force traces was very good. Calculation of total force using Stokes fifth order theory overpredicts the measured total force by 10%.
Ohmart & Gratz (1979)	Gulf of Mexico, Conoco Full Scale Test Structure	Hurricane storm waves $18<H<35$ ft $6.0<T<10.5$ s water depth, 177 ft	Vertical cylinder d = 36 in.	$K_c=5-17, R_e=3\times10^5-3\times10^6$, evaluated by measured velocity at test section.	mean value of 0.7 for $1\times10^6<R_e<3\times10^6$ 0.86 for $3\times10^5<R_e<1\times10^6$	1.5	Wave force coefficients were calculated based on kinematics measured by current meters 5 ft from force transducer. C_D, C_M showed considerable scatter. There was some sign of C_D dependence on R_e.

AUTHOR	LOCATION	SEA STATE	STRUCTURE	K_c and R_e	C_D	C_M	Reliability/wave theory
Morison et al (1950)	Laboratory	Linear sinusoidal waves $0.1<d/\lambda<0.5$ $4.8<d/H<18.2$	Vertical cylinder $0.01<D/\lambda<0.04$ $0.2<D/H<0.8$	$K_c=4$-25, $R_e=2\times10^3$-10^4 8.0×10^5, evaluated using measured velocity at test section	1.626 ± 0.414	1.508 ± 0.197	Measured moments and moments calculated using linear wave theory and constant C_M and C_D values derived for individual waves agreed well over a wave cycle. C_M and C_D did not correlate well with d/λ, D/λ or R_e.
O'Brien & Morison (1952)	Laboratory	Linear sinusoidal waves $0.2<H<0.4$ ft $0.6<T<2.2$ s $0.9<d<1.3$ ft	Spheres on bottom of water channel $0.030<D<0.125$ft	$K_c=1$-4, $R_e=1.9\times10^3$-7.8×10^3, evaluated using maximum orbital velocity at centre of sphere	0.8-3.0	0.9-1.6	Measured forces and forces calculated using linear wave theory and constant C_M and C_D values derived for individual waves agreed well over a wave cycle. Alternative derivation methods gave C_M values varying over 100% for the same wave and C_D value.
Keulegan and Carpenter (1958)	Laboratory	Linear sinusoidal standing wave $0.10<U_M<0.75$m/s	Horizontal cylinders and flat plates submerged under standing wave node $0.5<D<3.0$ in.	$K_c=2$-120, $R_e=4\times10^3$-3×10^4, evaluated from values of U_M given.	0.7-2.2 cylinders, 1.8-11.5 plates. Presented as functions of K_c.	0.6-2.6 cylinders, 1.1-5.0 plates. Presented as functions of K_c.	Agreement between the measured forces on the cylinders and those calculated using linear wave theory was excellent except near $K_c=15$, where the largest difference was about 20%. The agreement for flat plates was not so good. Phase variation was considered, but C_M and C_D departed significantly from mean values only for cylinders near $K_c=15$. Eddy shedding was related to variation in C_M and C_D, and to K_c.
Paape and Breusers (1967)	Laboratory	(a) Structure oscillated in still water $0.5<T<3.0$ s Semi-amplitude 0.01-0.20m (b) Linear sinusoidal waves $0.43<T<0.80$ s $0.007<H<0.075$ m d=0.300, 0.406, 0.555, 0.775m	(a) Horizontal cylinder and plate D=0.075m (b) vertical square piles D=0.025, 0.046, 0.063 m	(a) $K_c=0.8$-16.7, $R_e=7.7\times10^3$-2.7×10^4, evaluated using the amplitude of oscillation (b) $K_c=1$-10, $R_e=10^3$-7×10^5, instantaneous values at maximum force	(a) 0.5-2.0 cylinder, 3-13 plate. Presented as functions of K_c (b) Not considered	(a) 1.0-2.5 cylinder, 1-4 plate. Presented as functions of K_c (b) Not considered	Results of experiment (a) agreed with the results of Keulegan and Carpenter. Doubt was cast on the use of Morison's equation due to uncertainties in C_M and C_D. It was recommended that model wave force should be used in design with H/D as independent parameter. Wave theory was not considered.
Jen (1968)	Laboratory	Regular and irregular small waves $0.063<H<0.345$ft $0.9<T<2.0$ s d=3 ft	Vertical cylinder D=6 in.	$K_c=0.4$-2.2, $R_e=5.6\times10^3$-2.5×10^4, evaluated using Airy theory deep water approximation.	Drag negligible	2.0	Linearized force r.m.s. values were in good agreement with the measured values, justifying the neglect of drag. Spectral analysis of two irregular waves also gave $C_M=2.0$

AUTHOR	LOCATION	SEA STATE	STRUCTURE	K_c and R_e	C_D	C_M	Reliability/wave theory
Rance (1969)	Laboratory	Pulsating water tunnel	Vertical cylinders $0.025<D<0.3$ m	K_c=9-230, from a/D values quoted; R_e = 4×10^3-7×10^5, instantaneous values at maximum force.	0.4-7.0 as a function of a/D and R_e, 0.4-1.7 for K_c>60.	2.0	Assuming a constant value for C_M reduced the scatter in C_D. Drag was dominant; results were good only for K_c greater than about 60. a/D was shown to affect critical R_e significantly. Transverse lift force was also given as a function of a/D and exceeded in-line force at R_e less than 10^4. Wave theory was not used.
Shank and Herbich (1970)	Laboratory	Linear sinusoidal waves $1.5<\lambda/d<6.0$ $0.01<H/\lambda<0.11$ d=13,18,24 in.	Rectangular and semi-cylindrical model oil storage tanks D=8 in.	K_c=0-11, R_e=2×10^3-2.6×10^6, evaluated using maximum orbit velocity at centre of object.	Drag negligible	1.2-2.2 Optimum value 1.8	Agreement between measured forces and forces calculated using linear wave theory was good. Force increased with H/λ and λ/d, but C_M was independent of these parameters.
Gusbielles et al (1971)	Laboratory scaled 1:30 on Froude's scale law	Linear sinusoidal and irregular waves 2<H<16 m 6<T<18 s d=20 m Full-scale values	Vertical cylinder D=1 m Full-scale	K_c=6-105, R_e=9.2×10^5-5.0×10^6 full scale, R_e=5.6×10^3-3.0×10^4 model scale	0.6-3.0 Values in irregular waves considered to be higher.	0.8-2.1 Values in irregular waves considered to be higher.	The actual C_M and C_D range of values varied with the methods of derivation, which included linear, Stokes third and fifth order wave theory and stream function wave theory. Use of C_M and C_D obtained from Keulegan and Carpenter's curves from K_c values resulted in a maximum difference of 10% between measured and calculated local forces. Several C_M and C_D pairs were shown to predict the same force.
Johnson (1972)	Laboratory	Linear sinusoidal waves $11.7<d/H<65.6$ $0.4<d/\lambda<2.5$	Vertical cylinders D=0.25,0.50, 0.67 ft, top 3 ft below still water level.	K_c=1-12, R_e=3.5×10^4-1.6×10^5	Drag negligible	2.0	The measured forces agreed to within 20% of the forces calculated using linear wave theory. A theoretical formula for the wave force was derived assuming drag was negligible and C_M = 2.0.
Chakrabarti and Tam 1973)	Laboratory	Linear sinusoidal waves 3<H<10 in. 1.0<T<3.5 s d=47.25 in.	Vertical cylinder D=81 in.	K_c=0.1-0.7, R_e=10^5-10^6	Drag negligible	2.0 for $D/\lambda \approx 0.2$	Agreement between theoretical and experimentally measured forces was excellent. Wave forces were evaluated by diffraction analysis, using linear wave theory.
Mercier (1973)	Laboratory	Low speed constant stream d=10 in.	Vertical cylinder oscillated parallel and transverse to stream D=0.5,1.0 in.	K_c not considered. R_e=6×10^3-1.3×10^4, stream velocity value (U_o), interaction with oscillation not considered.	1.0-2.5 transverse oscillations, 1.0-5.0 parallel oscillations	0-1.5 transverse oscillations, 0.2-0.8 parallel oscillations	C_M and C_D were found to depend on the velocity and direction of the stream and the amplitude of oscillation. Drag force correlated with fD/U_o (f=frequency). Wave theory was not used.

AUTHOR	LOCATION	SEA STATE	STRUCTURE	K_c and R_e	C_D	C_M	Reliability/wave theory
Garrison et al (1974)	Laboratory model scale 1:120	Linear sinusoidal waves simulating full-scale conditions of 21<H<29 m 14<T<17 s d=120 m	Model of Condeep oil production platform structure. D=12 m for towers at water line	K_c=0.5, R_e=3x10^7-9x10^7 full scale, R_e=2.3x10^4-6.9x10^4 model scale	1.0 Assumed value	2.0 Assumed value	Agreement between calculated and measured forces and moments on the model was excellent. Diffraction analysis using linear wave theory was applied to the large base to obtain the velocity field for the platform supporting towers. The drag force was very small.
Sarpkaya and Tuter (1974)	Laboratory	One-dimensional simple harmonic flow Amplitude = 11 in. T=2.86 s d=20 in.	Horizontal cylinders extended across the horizontal limb of a U tube 1.0<D<2.5 in. Spheres hung on wires in the horizontal limb of a U tube 1.25<D<3.975 in.	K_c=0.50, R_e=0-10^4, evaluated using the amplitude of the simple harmonic flow.	0.0-2.1 cylinder, 0.0-0.8 sphere. Presented as functions of K_c	0.8-2.1 cylinder, 1.0-1.5 sphere. Presented as functions of K_c	Lift forces up to 1.5 times drag force were measured up to K_c values of about 20. Measured and calculated forces agreed to within 15%; the difference was largest at K_c=12 for cylinders and between K_c=12 and 22 for spheres. Generally agreement was excellent.
Chakrabarti et al (1975)	Laboratory	Linear sinusoidal waves 4<H<13 in. 1.5<T<3.0 s d = 5 ft	Cylinders held at various inclinations, in line with and normal to the waves D=3,5,7.5 in.	K_c=0-20, R_e=5x10^3-5x10^5, calculated using maximum horizontal velocity averaged over the length of the cylinder.	0-2.5	1.0-2.5	Large scatter in C_M and C_D values. Morison equation used in three-dimensional vector form with velocity component normal to the axis of the cylinder. Measured and calculated mean forces agreed to within 10% using C_M and C_D values for individual waves.
Sekita (1975)	Laboratory	Small amplitude regular waves 5<H<42 cm 0.9<T<5.0 s 0.005<H/λ<0.1 d=133 cm	1/60 scale model of jacket structure with cross framing, with 15 conductor tubes and with no conductor tubes, at various incidences to the flow.	K_c=10-100, R_e=10^3-3x10^4, evaluated using maximum velocity at still water level as given by Stokes fifth order theory and the diameter of the main column.	0.6 Representative of whole structure; values smaller when conductor tubes included.	1.6 Representative of whole structure; values smaller when conductor tubes included.	C_M and C_D showed a markedly different correlation with K_c from that obtained by Keulegan and Carpenter. Morison's equation was used in three-dimensional vector form with velocity component normal to the axis of the cylinder. Current drag was considered separately. Application of model results to prototype is uncertain.

AUTHOR	LOCATION	SEA STATE	STRUCTURE	K_c and R_e	C_D	C_M	Reliability/wave theory
Sarpkaya (1976)	Laboratory	One-dimensional simple harmonic flow T=5.272 s	Smooth and rough horizontal cylinders extended across the horizontal limb of a U tube, larger than that used in Sarpkaya and Tuter (1974).	K_c=0-200, R_e=10^4-7×10^5, evaluated using the amplitude of the simple harmonic flow. Frequency parameter $\beta_1=R_e/K_c$ and roughness Reynolds number $U_M k_r/\nu$ also shown to be important data correlation parameters.	0.5-2.0 Presented as functions of R_e, K_c, and k_r/D	0.7-1.9 Presented as functions of R_e, K_c, and k_r/D	Very little data scatter; lift coefficient and Strouhal number also found to be functions of R_e, K_c and k_r/D. Lift forces can be large and must be considered in design; Strouhal number varied between 0.15 and 0.45. Agreement between measured and calculated forces was excellent except between K_c values of about 10 and 20. These discrepancies were largely attributed to eddy shedding associated with large lift forces and shedding of single vortices.

APPENDIX B

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